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TITLE OF THESIS .... METEOROLOGICAL-HYDROLOGICAL RELATIONSHIPS
IN THE CYPRESS HILLS, ALBERTA - AN ATTEMPT
AT MODEL DEVELOPMENT FOR DISCHARGE
FORECASTING -

DEGREE FOR WHICH THESIS WAS PRESENTED .... MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED 1974

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METEOROLOGICAL-HYDROLOGICAL RELATIONSHIPS IN THE CYPRESS HILLS, ALBERTA
- AN ATTEMPT AT MODEL DEVELOPMENT FOR - DISCHARGE FORECASTING

BY

© RAYMOND KI WAI WONG

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND
RESEARCH IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

EDMONTON, ALBERTA

FALL, 1974

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled Meteorological-Hydrological Relationships in the Cypress Hills, Alberta - an attempt at model development for discharge forecasting -

submitted by RAYMOND KI WAI WONG

in partial fulfilment of the requirements for the degree of Master of Science

TO MY PARENTS,

who first inspired in me the desire to know,
this initial work of research is affectionately
dedicated

ABSTRACT

Meteorological data from observational sites in the Cypress Hills area were analyzed. Insufficient winter precipitation data made it necessary to estimate the monthly winter precipitation at these sites using observations from nearby stations with established precipitation records. The Thornthwaite 1957 procedure was used in providing estimates for various components of the water balance equation. The estimates of water surplus were compared with the measured runoff values, and in conjunction with topographical and climatic considerations, these estimated values were used in the production of water surplus maps. Data deficiency has caused some inaccuracy in the surplus patterns, but it is believed that the general trends of the isolines are representative of the actual situation. Multiple linear regression analyses were performed in order to look for statistical relationships between the meteorological and hydrological variables. Analyses were carried out on both annual and daily data. Significant relationships were found, but stable models suitable for prediction were not available. Relocation of meteorological stations, continuous records and improved network of stream gauges were recommended for more promising model formulation attempts.

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CHAPTER I

INTRODUCTION

Water is the best of all things
- Pindar, Olympian Odes I

I can foretell the way of celestial
bodies, but can say nothing of the
movement of a small drop of water
- Galileo Galilei

1.1 Hydrological Forecasting

Hydrological forecasting is necessary for the rational use of water resources and the control of hydrological hazards. It implies the application of hydrological principles to the estimation of the future behaviour of water bodies, with a specific problem in mind. It may range from short-range forecasting of river stage, to the prediction of freezing-up and melting dates, ice-cover thickness or long-term fluctuations of groundwater levels. There is no general formula in hydrological forecasting. Chow once reviewed sixty-six formulae developed for the prediction of peak runoff alone. It is often necessary to have a "custom-made" prediction method for each instance, for it is not uncommon to find spatial or temporal variations in the relationship between the same hydrological phenomenon and the same geological, physical geographical or meteorological controls.

Alekhin broadly categorizes the methods of streamflow forecasting into two major groups: (1) Hydrometric methods

and (2) Hydrometeorological methods. (Alekhin, 1964, p. 12). In the hydrometric approach, the balance between precipitation and losses are considered indirectly through hydrometric records, while hydrometeorological methods involve the consideration of precipitation and losses using meteorological observations. In the former approach, the temporal distribution of streamflow is examined independently. Since streamflow represents the balance between precipitation and losses, the variations in streamflow would also represent changes in the balance between precipitation and loss parameters. The major interest here is forecasting based on the autocorrelation amongst runoff values rather than the intercorrelation amongst several variables, which is the concern of the latter approach. In the hydrometeorological approach, meteorological parameters are used as predictors for streamflow changes, based on certain established interrelationships. In the hydrometric approach, the pattern of temporal variation of streamflow is identified, and forecasting is achieved by extrapolation.

1.2 A Hydrometeorological Approach: The Water Balance

When both meteorological and hydrological data are available, it is desirable to begin with the hydrometeorological approach by investigating first the nature of dependence of streamflow characteristics upon meteorological variables. Bernard Palissy, of the sixteenth century is believed to be the first person to state categorically that precipitation is the sole source of streamflow. (Biswas, 1970, p. 151). But

streamflow characteristics are also under the influence of other meteorological, geological and physical geographical controls, which through diverse channels, determine the efficiency in which precipitation becomes streamflow. For example, temperature determines the state of water and thus the ability of water to flow and the form of precipitation. Being related to kinetic energy and surface tension, it determines the rate of evaporation. It is also related to the ability of air to hold moisture. Wind aids evaporation by advective transport of water vapour. The physical geographical parameters such as channel slope, basin size, basin shape and stream-system characteristics affect the amount of surface runoff and the slope of the hydrograph limbs. The geological characteristics of the basin influence the shape of hydrograph by affecting such factors as surface retention, the rate of groundwater flows and interflow and the size of groundwater reservoirs. All of these parameters may also combine to affect the vegetative cover of the basin and hence control the amount of water loss through transpiration.

In seasonal streamflow forecasting, one may neglect the effect of changes in the geological and physical geographical factors by assuming, for practical purposes, that they are constant for the time scale involved. The changes in the geological and physical geographical factors are far too slow as compared with those of the weather elements. For any suitable forecasting period, the variations in streamflow

characteristics would largely be responses to variations in the meteorological controls.

1.3 Objectives

The objectives in the present study are to examine the meteorological-hydrological relationships in the Cypress Hills of southeastern Alberta and to attempt a model formulation for discharge forecasting. The meteorological-hydrological relationships of an area are often studied, but unfortunately, the underlying laws are poorly known. It is suggested that the general effects of meteorological parameters are more clearly defined on an annual basis than for a shorter period, (Mustonen, 1967, p. 123), and that it is a misleading concept to rely on pure meteorological observations for long-range forecasting of water supply (and hence streamflow). (Yevjevich, 1968, p. 228). This is intended to be a study of annual spring runoff relationships with an attempt to develop a seasonal discharge forecasting model.

There are several reasons for the choice of the study area. Laycock, in his study of the water deficit patterns in the prairie provinces using Thornthwaite's 1948 procedure, found that southeastern Alberta and southwestern Saskatchewan contain the driest areas in the prairies, with high potential evapotranspiration and low precipitation rates. (Laycock, 1967). But it is indicated in the pattern of water balance that the Cypress Hills area is an island-oasis of compara-

tively humid conditions in a semi-arid surrounding. A deeper understanding of the hydrology of this area will lead to better water resources planning, which in turn leads to greater development of some areas within the region for agricultural, industrial, recreational and wildlife purposes. There are also difficulties with respect to the allocation to the United States of water from some of the international streams in the area, and more information regarding the water resources of the area is needed.

The topography of the area is ideal for studying the effect of altitude on the water balance pattern. This will be investigated in the present study. The Cypress Hills Plateau rises above the surrounding plain high enough to impose orographic uplift upon the passing air masses and this is abrupt enough to provide a good contrast within a small horizontal distance. Also the hydrographical patterns of the area are favourable for a study of the effects of slope aspect on the water balance.

Finally, the availability of meteorological and hydrometric data, many of which have only recently been available and which have not yet been analyzed, provide further impetus towards the initiation of this study.

CHAPTER II

THE STUDY AREA

> The Cypress Mountains formed indeed a great contrast to the level country through which we were travelling. They are covered with timber......... the soil is rich and the supply of water abundant......... they provide a perfect oasis in the desert we have travelled.
>
> \- Capt. John Palliser 1859

2.1 Introduction

At present, the Cypress Hills area is the site for several parks. The surrounding land has been much developed since the pioneer days and still carries considerable potential for more future development in recreation and agriculture. Geomorphologically, the plateau itself is an erosional remnant which was high enough that its upper portions were not glaciated during the last glacial advance. It now stands as the centre of a modified radial drainage pattern over a surrounding till-covered rolling plain. The climate is semi-arid with long cold winters and short bright summers. Being in the rainshadow of the Rockies, the surrounding plains have only less than moderate precipitation, rising to more humid conditions in the summit areas of the plateau, which is the major source of runoff for several prairie streams.

2.2 Location and Access

The study area is situated mainly in the southeastern portion of the province of Alberta and includes the western

half of the Cypress Hills plateau. It is about 40 miles to the southeast of Medicine Hat, the nearest major urban centre. Its southern limit lies within 20 miles of the international border, and the Alberta-Saskatchewan boundary roughly marks its eastern fringe. (See Map 2.1). There are eight river basins included in the present study and all of them lie within 30 miles of the Cypress Hills plateau. These eight basins cover a total area of over 1250 square miles, bounded at its extremities by latitudes $49^\circ\ 12'$ N and $49^\circ\ 57'$ N and longitudes $110^\circ\ 57'$ W and $109^\circ\ 55'$ W.

The study area is easily accessible by motor routes from all directions. The Trans-Canada Highway runs along its northern edge, from which Highway 48 leads southward to Elkwater, the Cypress Hills and eventually the international border. From the west, Highway 61 reaches as far as Manyberries. The whole area is served by a good network of all weather roads.

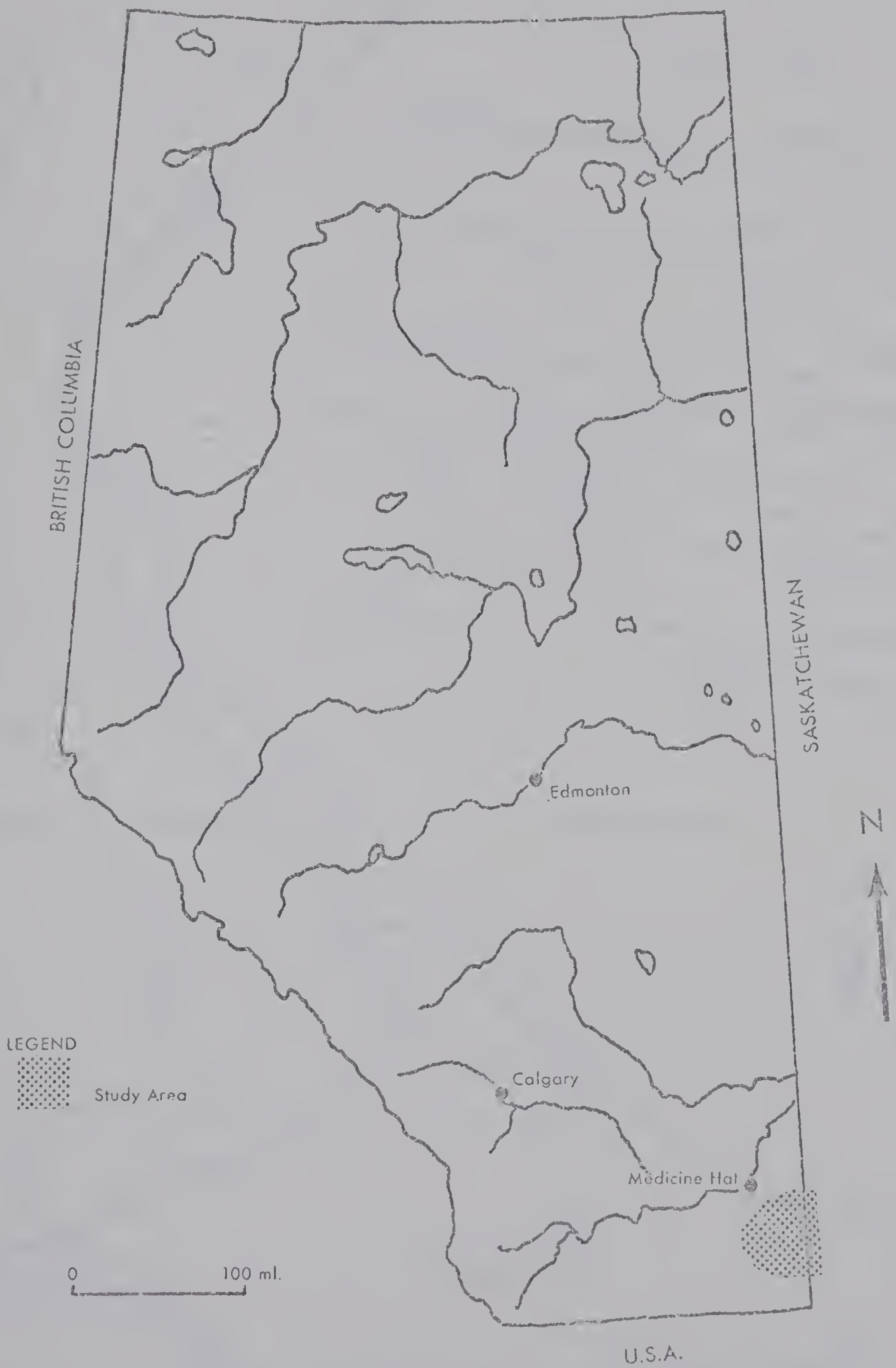
2.3 Geology

A detailed study of the surficial geology of the area was carried out by J.A. Westgate. (Westgate, 1968). It was found that sandstone or shale formations underlie the entire low level area. The major ones are (1) Bearpaw Formation (2) Eastend Formation (3) Ravenscrag-Frenchman Formation (4) Oldman Formation and (5) Cypress Hills Formation. Their distributions are shown on Map 2.2. The Cypress Hills plateau

MAP 2:1

LOCATION OF STUDY AREA

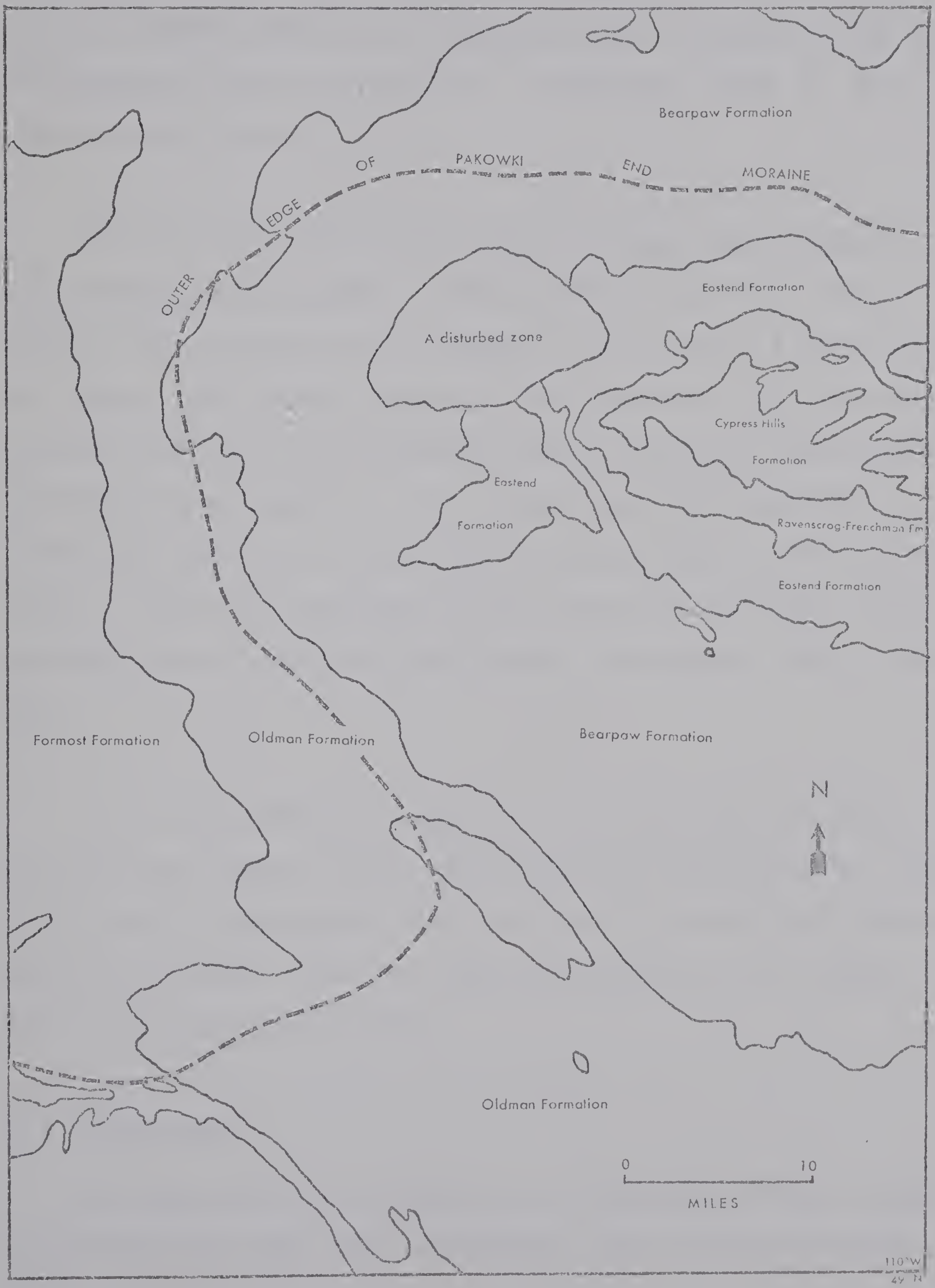
IN ALBERTA



MAP 2:2

BEDROCK STRUCTURE OF STUDY AREA

(after Westgate 1968)



is composed of conglomerate. The texture of the overlying surface material is affected by the nature of the underlying bedrock. Westgate has shown that a change in bedrock structure is almost immediately accompanied by a change in the graphic mean of the overlying till. (Westgate, 1968, p. 46 & Figure 20 & Figure 21).

The till has essentially clay to clayey loam texture. The average graphic mean is from 0.055 to 0.094 mm. The crest of the Cypress Hills plateau is covered by a thin veneer of loess. The loessic origin of this material has been verified by the grain size gradation and by studying the mineral content of the deposit. It is found that the hornblende within the deposit is identical to those found in the surrounding tills. Since ice could not be the transporting agent, their aeolian origin has been established. (Westgate, 1968, p. 56-57).

It is described as "atypical" for the median diameter of the loess deposit to be within the fine sand section, while it is easily conceivable that frost action could have elevated quartzite pebbles from the underlying Cypress Hills conglomerate into the loess layer.

2.4 Topography

The Cypress Hills plateau is a dissected plateau rising some 2000 feet above the surrounding till-covered prairies.

The highest point on the plateau is in excess of 4800 feet a.s.l. and is about 2700 feet higher than Medicine Hat. The highest portion is on the western extremity of the plateau and the elevation drops to less that 4500 feet at the provincial boundary in the east. The upper parts of the plateau were not glaciated during the last glaciation. It now stands out as an unglaciated erosional remnant of higher level tertiary plains in an area of ground moraine, hummocky moraine and ridge end moraine.

The plateau ends abruptly in the north and the west while in the south, it slopes gently into the lower level plains. At the steeper parts of the north-facing and west-facing slopes, a drop of over 1000 feet is achieved within two and a half miles, while in the south-facing slope, the same difference in elevation is found over a horizontal distance of over six miles, with fairly even gradient throughout. The hydrometric gauge on Battle Creek at the ranger station (about three miles upstream from Fort Walsh) marks the eastern extremity of the study area. It is still within the high level areas of the Cypress Hills plateau.

The plateau is dissected by numerous stream which tend to form steep-sided valleys on the northern and western slopes because of the greater gradients. These streams flow through large areas of till covered plain, having but rolling relief typical of morainic areas. There is still a general tendency

for the surrounding till plain to slope away from the plateau. At the northern and western extremities of the study area, the elevations are 2500 feet a.s.l. and 2700 feet a.s.l. respectively, while at the southern edge, an elevation of over 3100 feet a.s.l. is attained.

The continuity between the plateau and the surrounding plain is disturbed in various places by deep coulees. These are abandoned ice marginal channels, which today may or may not carry significant streamflow. An example is the Medicine Lodge Coulee.

2.5 Climate

In simple terms, the climate of southeastern Alberta can be described as having hot dry summers and cold sharp winters. It is characterized by frequent chinook effects and little maritime influence due to the presence of the Rocky Mountains. The mean annual precipitation of the plains area is about thirteen inches, while at the crest of the plateau, mean annual precipitation may be twenty inches or more. The difference in evapotranspiration rates between the lower level plains and the plateau crest is another element contributing to the climatic contrast, resulting in different water balance conditions between the plains and the crest levels of the study area.

At the lower levels, the average annual precipitation range is from thirteen inches in the north to less than ten

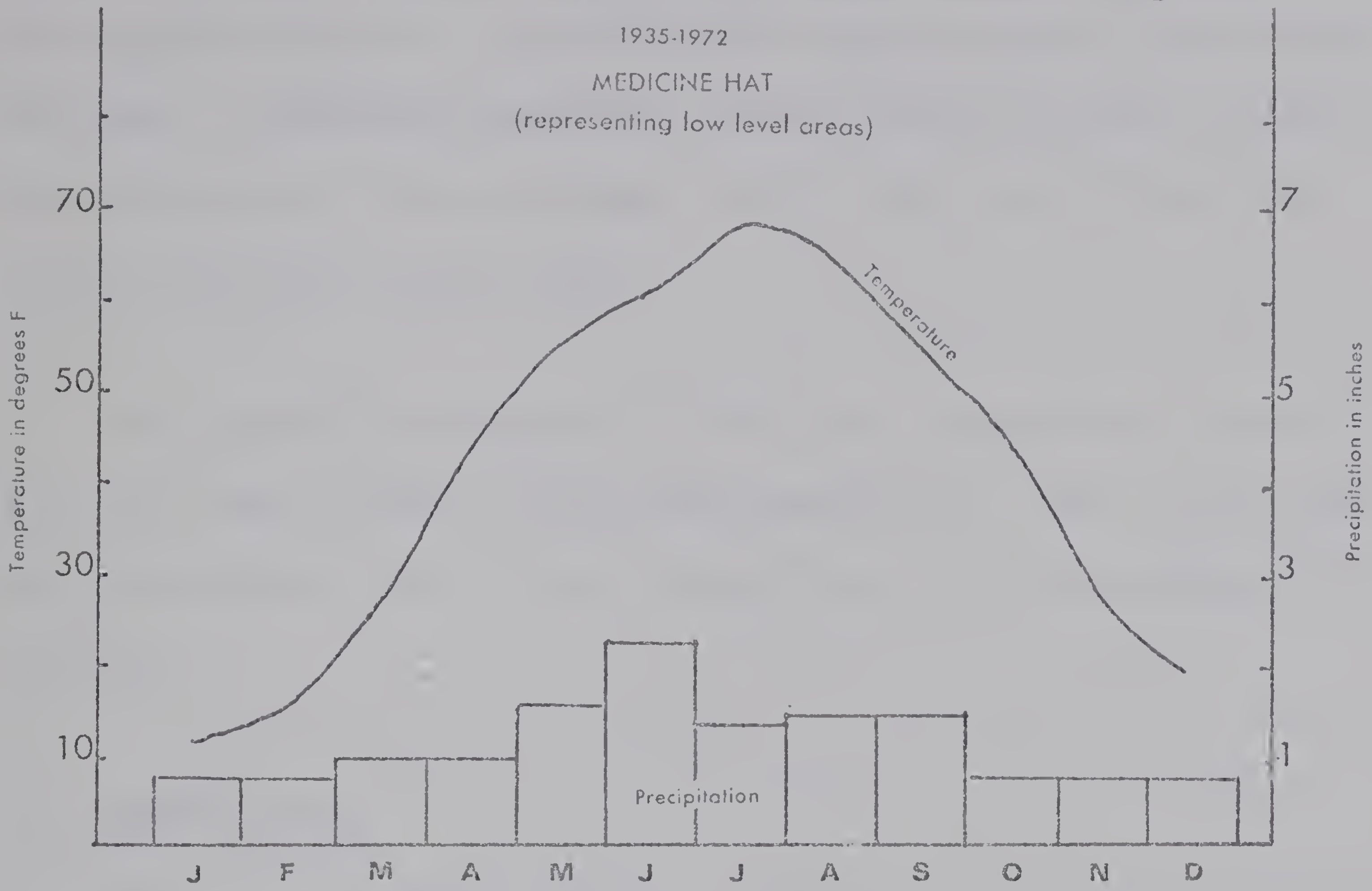
inches in the area south of the plateau. This is probably due to a rainshadow effect created by the orientation of the Cypress Hills plateau. In general, maximum precipitation occurs during summer. Winter precipitation is comparatively low and is largely in the form of snow.

The mean annual temperature at Medicine Hat and the Canada Department of Agriculture Research Station near Manyberries (from here on, this will simply be referred to as Manyberries CDA.), the two meteorological stations with established records lying to the north and to the south of the study area, are 41.5^{0}F and 39.9^{0}F respectively. From the available records, the crest levels have an annual mean temperature of 36^{0}F. It is difficult to compare this value to those of Manyberries CDA and Medicine Hat because of the comparatively short period of available records for the crest levels. Assuming a normal lapse rate of 3.5^{0}F per 1000 foot, the crest level mean annual temperature may seem a bit high. The difference may be caused by greater chinook frequency or non-representativeness of the available period of record. The annual march of long term average monthly temperature indicates a minimum in January and a maximum in July. The average monthly temperature and precipitation at both high and low levels within the study area are shown in Figure 2.1.

Despite subfreezing average winter temperatures, there are occasional warm spells due to the chinook effect. This

FIGURE 2:1

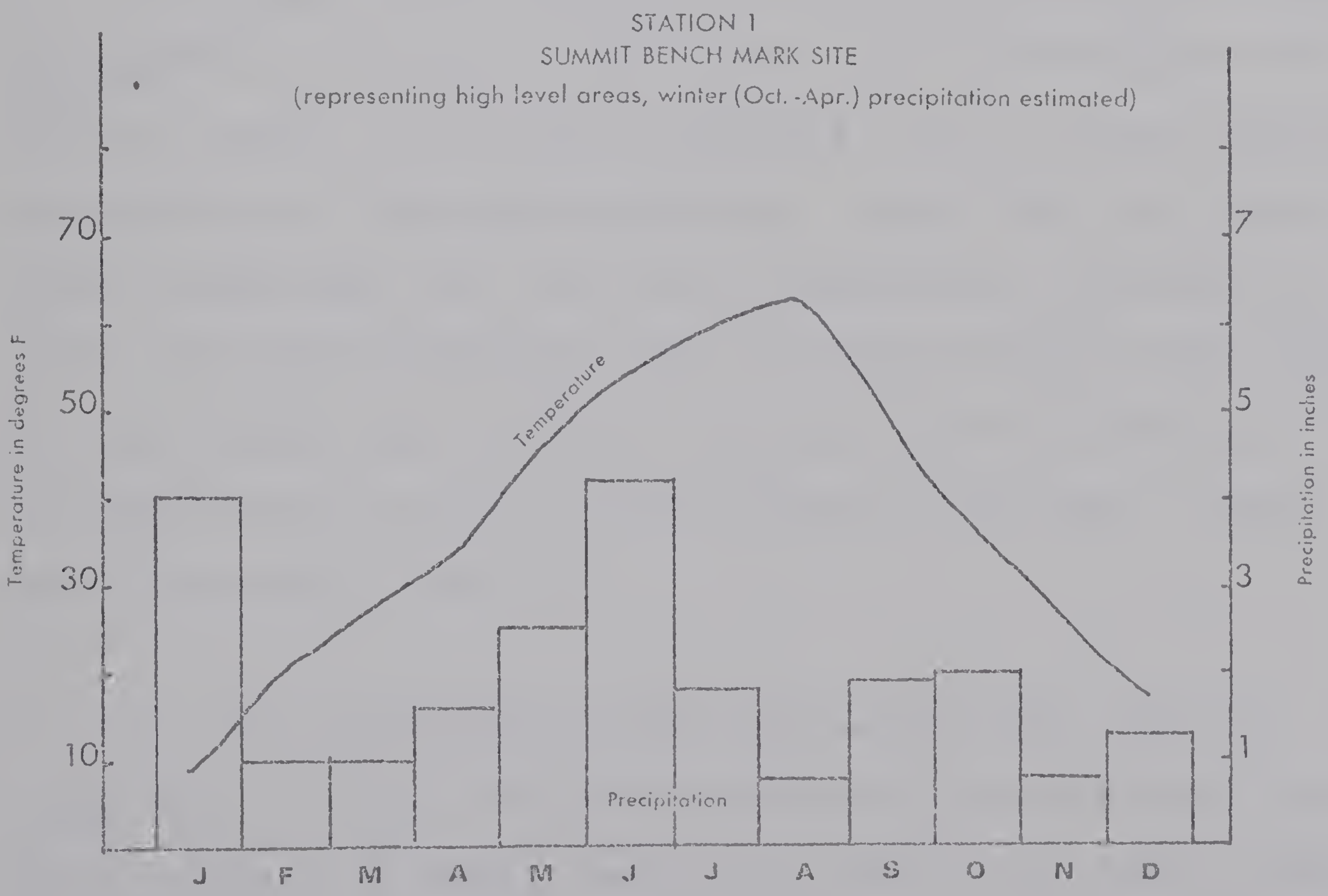
AVERAGE MONTHLY PRECIPITATION AND TEMPERATURE



1935-1972

MEDICINE HAT

(representing low level areas)



STATION 1

SUMMIT BENCH MARK SITE

(representing high level areas, winter (Oct. -Apr.) precipitation estimated)

often leads to melting of the snowpack in winter, although significant melting does not usually occur until spring. The summer maximum in precipitation coincides with the summer maximum in evapotranspiration and the result is that effective precipitation is much reduced. It is less so at the higher levels than the plains area.

The natural vegetation of the area consists of typical prairie flora, such as grass and sagebrush. Most trees grow on the northern ubac slope (shady slope) of the Cypress Hills plateau.

2.6 Hydrography

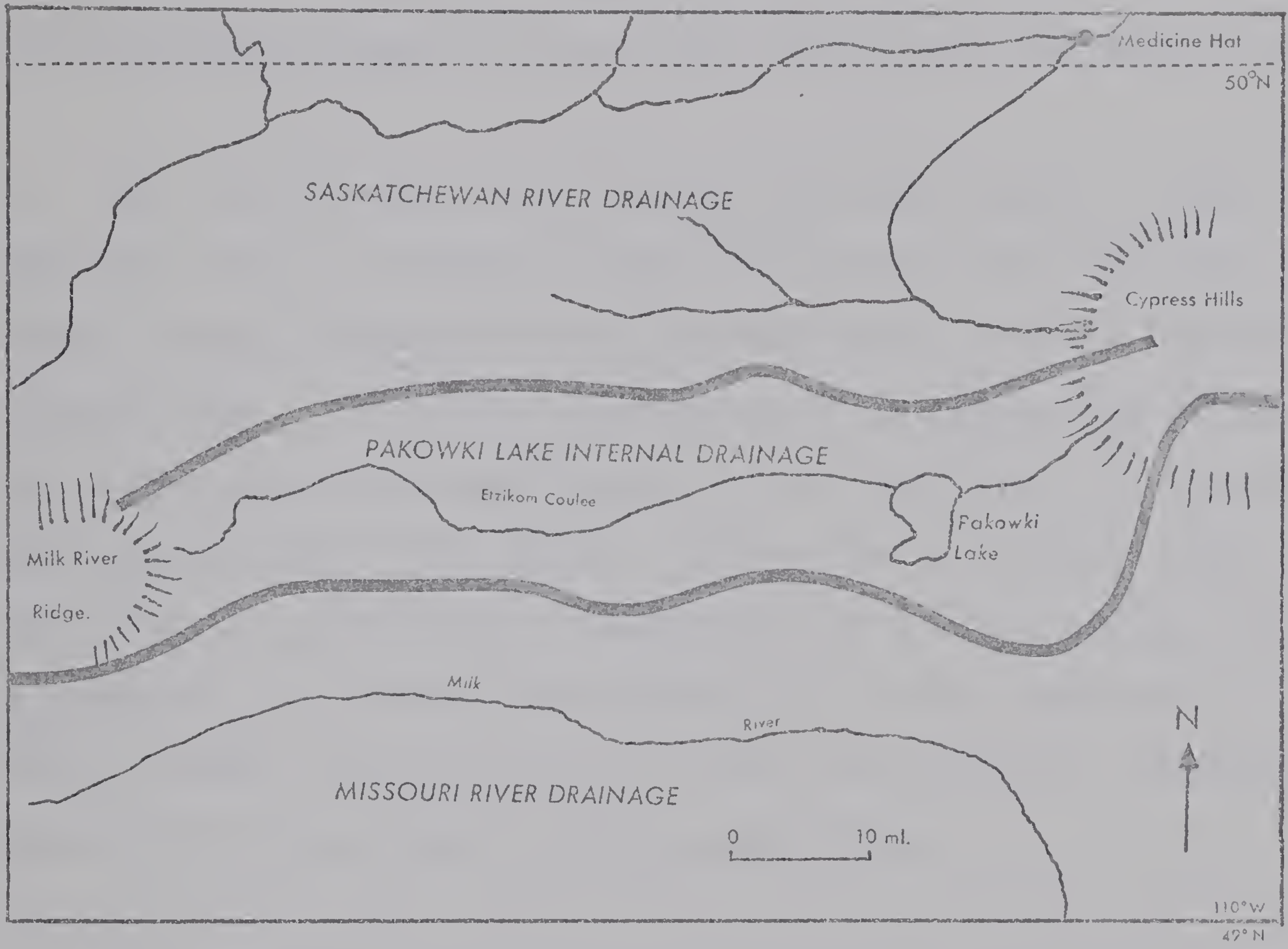
The Cypress Hills plateau, with its more humid conditions and higher elevations, is the source region for a number of prairie streams, which form a modified radial drainage pattern surrounding the conglomerate upland. Within the study area, these streams may flow into one of three major drainage systems: (1) The Saskatchewan River Drainage System to the north, (2) The Pakowki Lake Internal Drainage System to the west, (3) The Missouri River Drainage System to the south. These are illustrated in Map 2.3.

(1) The Saskatchewan River Drainage System: In the study area, streams which flow into this system from the Cypress Hills plateau are Mackay Creek, Ross Creek, Gros Ventre Creek, Bullshead Creek and Peigan Creek. Both Bullshead Creek and

MAP 2:3

DRAINAGE SYSTEMS IN SOUTHERN ALBERTA

(after Meyboom 1960)



Gros Ventre Creek flow northwestward from the Cypress Hills plateau and then turn east. Gros Ventre Creek later joins Ross Creek. Mackay Creek flows northward into a series of lakes while Peigan Creek drains westward first and then turns into Seven Persons Coulee. In this system, the drainage basins which will be examined in the present study are those of Gros Ventre Creek, Peigan Creek, Ross Creek and Mackay Creek.

(2) The Pakowki Lake Internal Drainage System: Manyberries Creek, Irrigation Creek and Ketchum Creek are the major streams flowing from the Cypress Hills plateau toward Pakowki Lake. The whole drainage basin is sandwiched between the Saskatchewan Drainage System to the north and the Missouri Drainage System to the south. To the west of Pakowki Lake, the basin is practically bisected by the Etzikon Coulee, an abandoned river channel now occupied by ribbon lakes and a small stream, leading into the drying Lake Pakowki. Manyberries Creek will be involved in the present study.

(3) The Missouri River Drainage Basin: The major stream in southern Alberta that belongs to this drainage system is Milk River, which turns south into the United States before reaching the longitude of the western extremity of the Cypress Hills plateau. Other streams flowing south from the plateau are also international streams. They include Lodge Creek, Battle Creek, Middle Creek and Sage Creek. All of them are parts of the Missouri River System .

There are also numerous sloughs, lakes and reservoirs. These water bodies influence local microclimate and are important to wildlife and recreation.

2.7 Hydrology

2.7.1 Surface Runoff

To illustrate the nature of streamflow in this area, the long term average annual hydrographs of five selected gauges are shown in Figure 2.2 to Figure 2.6. This selected sample includes gauges on streams flowing into each of the three major drainage systems. Basin area ranges from 75 square miles to 342 square miles and elevation ranges from low level prairie drainage (about 3000 ft. a.s.l.) to high level basin on the crest of the Cypress Hills plateau (above 4000 ft. a.s.l.).

It can readily be seen that the peak discharge occurs during spring in all streams and discharge rapidly drops down to low values for the rest of the year. The occurrence of spring snowmelt may take place any time from late February to May, dependent upon the temperature condition of the particular year in the particular basin. Usually, it is during April when large scale melting occurs. Occasionally this may happen in May or March or even February. This probably explains the slope change on both the rising limbs and the recession limbs of the hydrographs. Such slope changes

FIGURE 2:2

AVERAGE MONTHLY DISCHARGE AT GAUGE 1

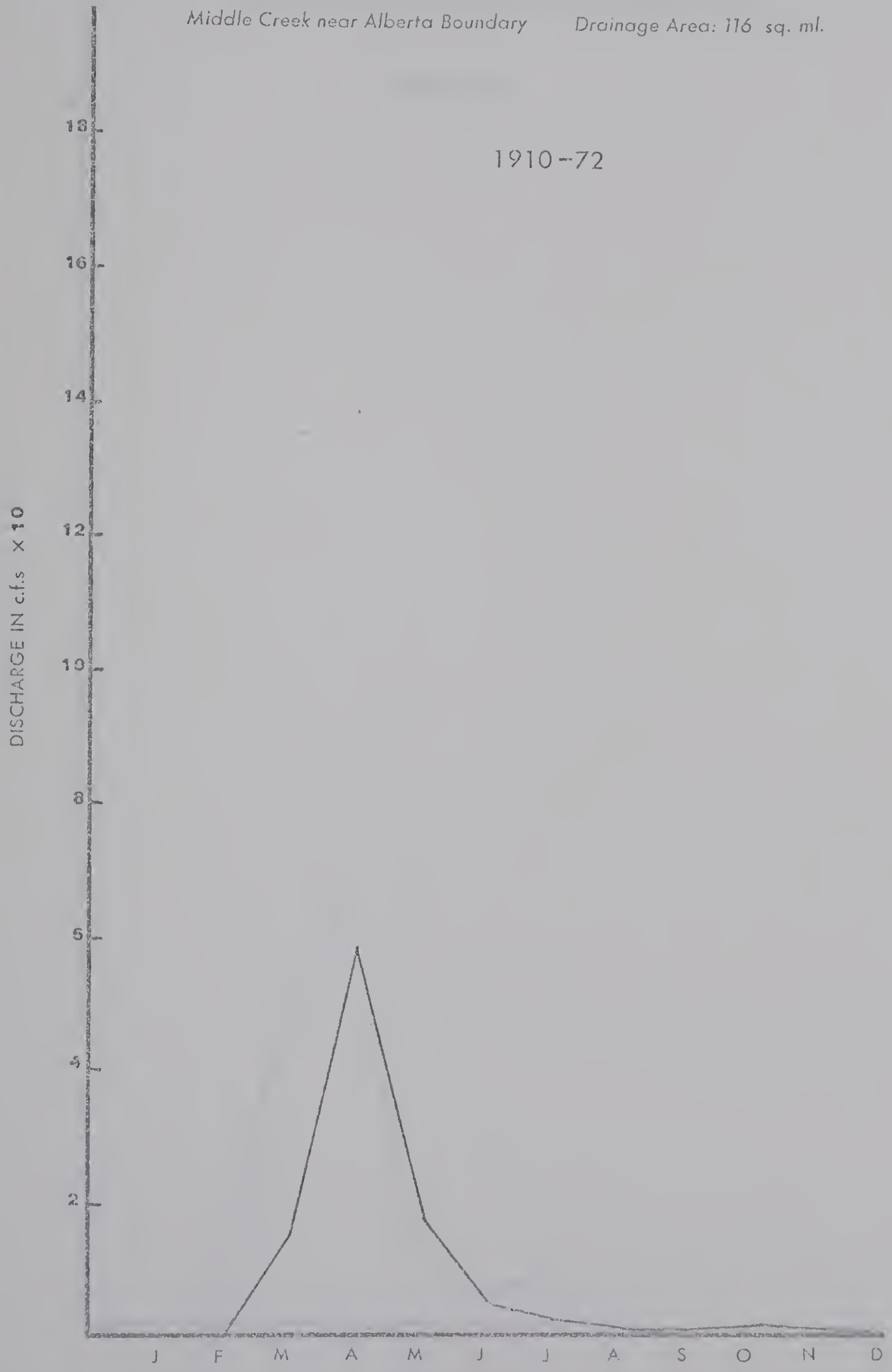


FIGURE 2:3

AVERAGE MONTHLY DISCHARGE AT GAUGE 4

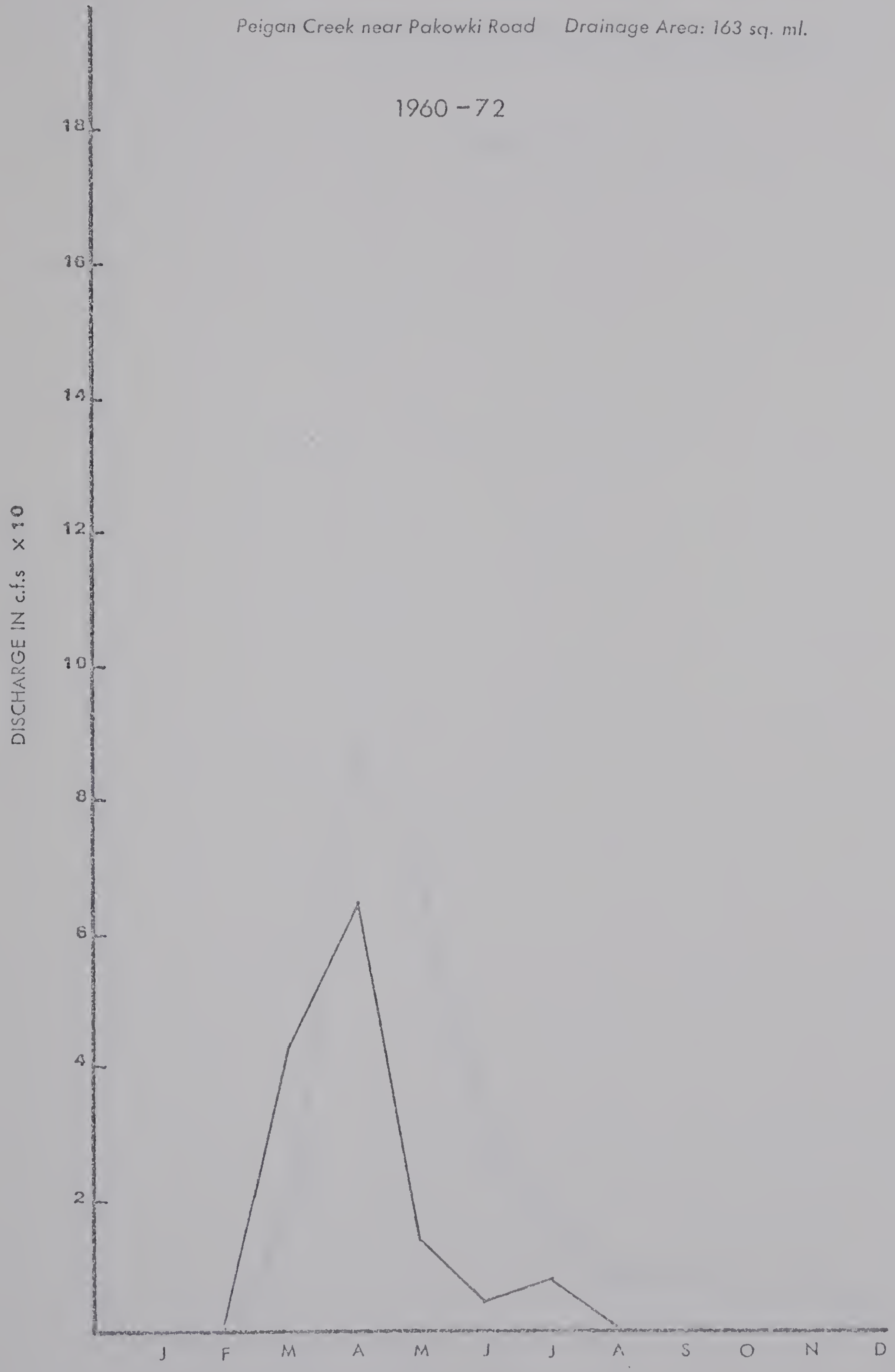


FIGURE 2:4

AVERAGE MONTHLY DISCHARGE AT GAUGE 5

Battle Creek at Ranger Station. Drainage Area: 75 sq. ml.

1950 – 72

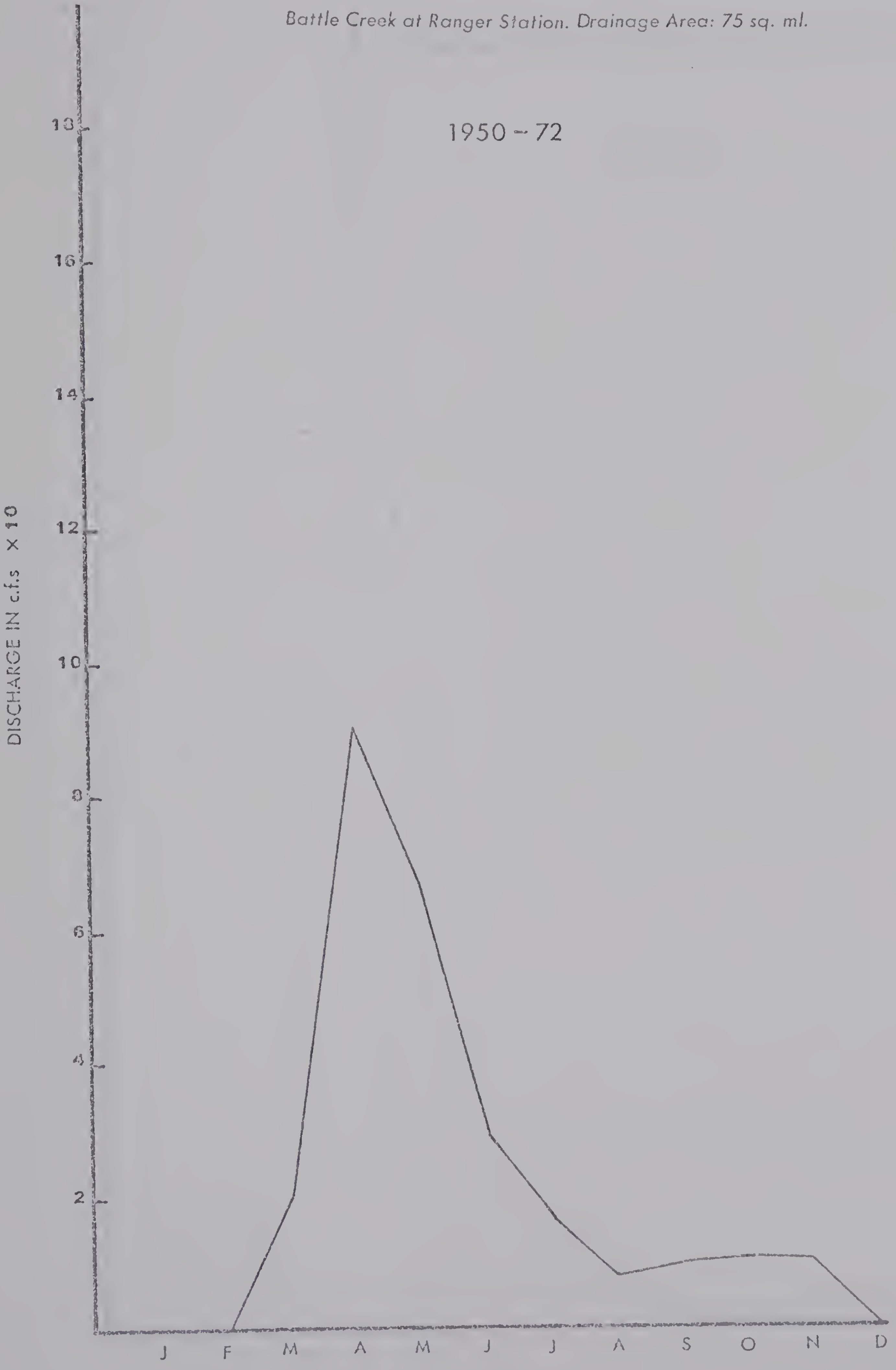


FIGURE 2:5

AVERAGE MONTHLY DISCHARGE AT GAUGE 6

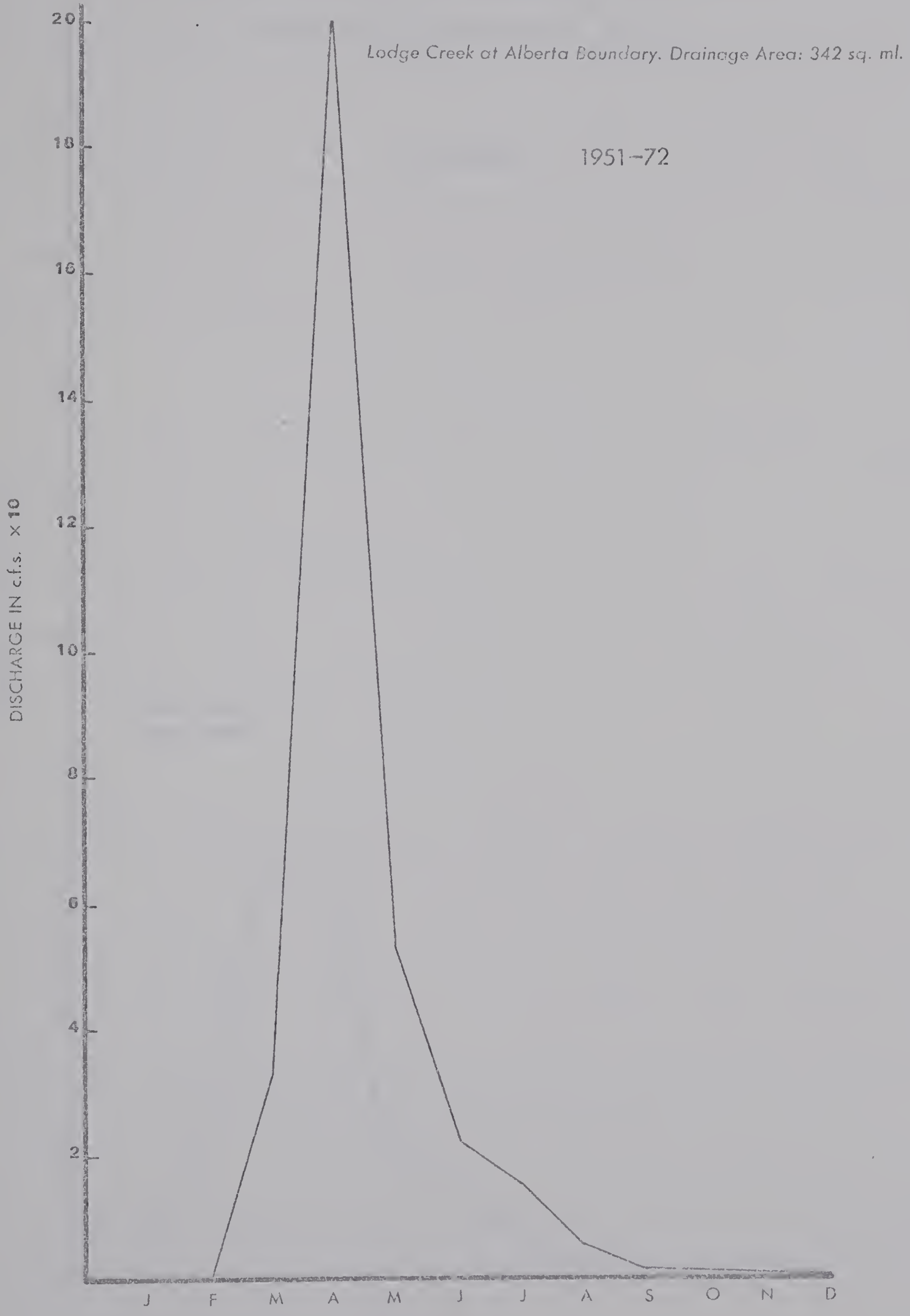
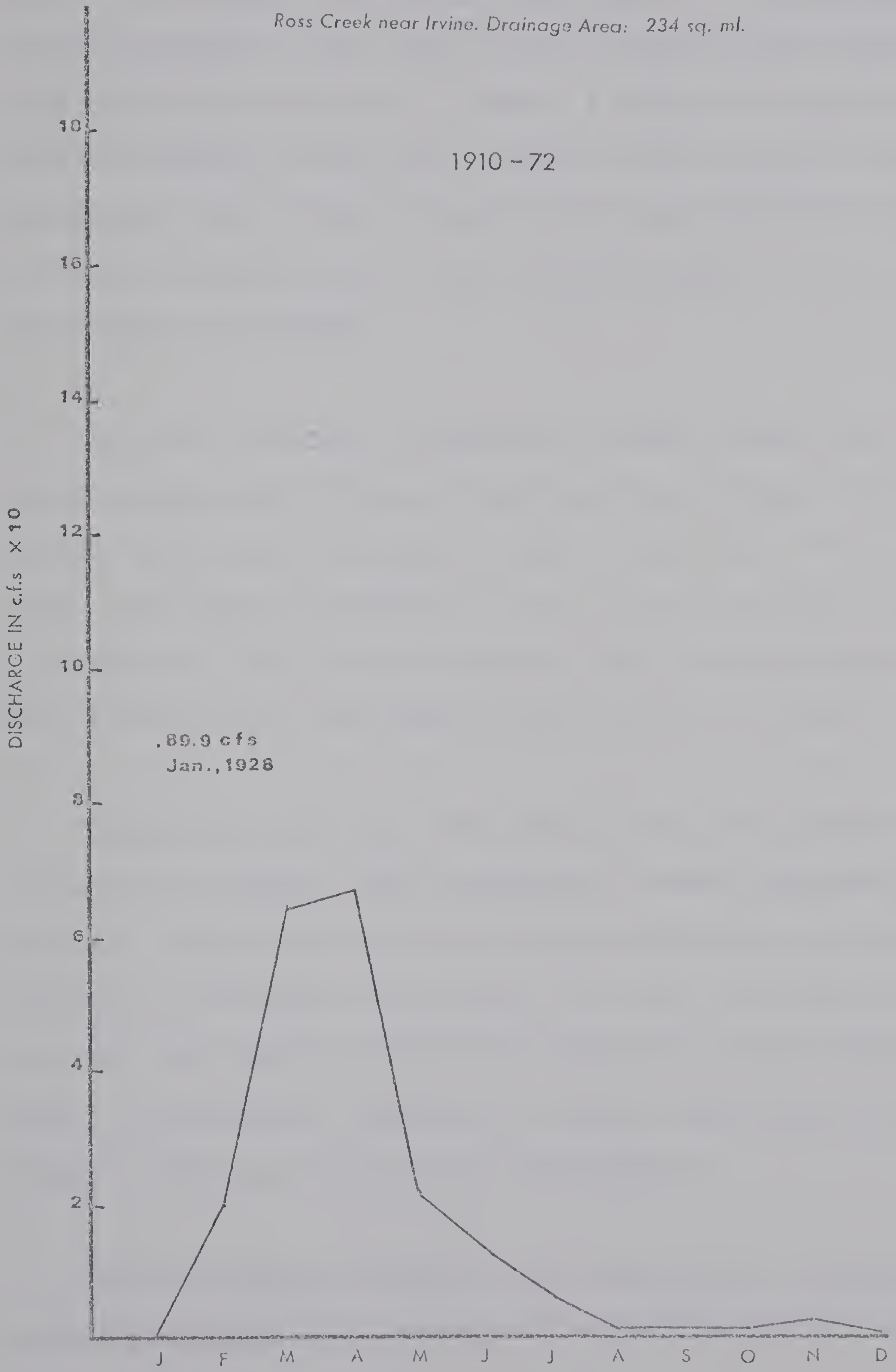


FIGURE 2:6

AVERAGE MONTHLY DISCHARGE AT GAUGE 7



may be interpreted as due to groundwater recharge or discharge prior or subsequent to the occurrence of the discharge peak. On a long term average hydrograph, a likely cause of such inflection points would be the temporal distribution in peak discharge occurrence. Hence, a higher frequency of peak discharge in April will cause an April peak in the average hydrograph, and a lower frequency of peak discharge in March or May will give a lower value of discharge on the average hydrograph accordingly.

In some occasions, pronounced chinook effect may lead to large scale winter floods. For example, a January discharge of 89.9 c.f.s. was recorded at Ross Creek near Irvine in 1928. The daily discharge of this particular month reached a maximum of 512 c.f.s. on January 10th. The average monthly peak discharge for the gauge is 67.8 c.f.s. in April.

Anomalous cases like this are results of synoptic meteorological phenomena, which determine chinook frequency and intensity. Since melting of such magnitude does not occur frequently in mid-winter and since it is not the purpose of the present study to be involved with synoptic scale investigations, relationships leading to chinook occurrences and occasional winter melting will not be examined.

Spring snowmelt runoff is the major factor shaping the annual hydrograph of streams within the study area. River

discharge due to spring snowmelt is by far the largest contribution to streamflow and it often overshadows the contribution from summer storms. For many smaller streams, spring snowmelt runoff is the sole source of streamflow. High summer evaporation rate so greatly reduces, and in some instances, completely eliminates the effective summer precipitation that it is not uncommon to find dry streams during the late summer months. Furthermore, high evapotranspiration rates during the summer months also make the relative maximum in discharge produced by the summer maximum in precipitation more insignificant in comparison to the peak discharge due to snowmelt. This is at least true in an average hydrograph.

There is also a small relative maximum (secondary peak) in discharge during early winter in some basins, while in others, such a relative maximum is not so conspicuous. A probable factor causing such secondary peaks is reduced evapotranspiration, which manages to increase the discharge by a small amount despite reduced precipitation.

Reduced evapotranspiration rates and greater precipitation at the higher levels of the Cypress Hills plateau are the factors leading to greater discharge during late summer and early fall months as measured at Battle Creek Ranger Station. (See Figure 2.4). Late summer and fall discharge is greatly reduced in other basins where the catchment area consists of

a considerable proportion of low level plains.

It is noteworthy that the annual discharge rates of the basins under study bear little systematic relationship to the sizes of the basins. This indicates a disproportionate distribution of surplus or deficit regions among the basins. It is one of the aims of the present study to provide water balance patterns for the area, and it suffices to note here that, while it is obvious that much of the surplus area would concentrate at the crest levels of the Cypress Hills plateau, it remains an interesting exercise to more specifically delineate the water balance zonation.

2.7.2 Groundwater Hydrology

Groundwater discharge in the study area becomes a major source of streamflow after the spring surface snowmelt runoff, which has by far the greater contribution to the total annual discharge. In the larger basins, where considerable portions of the basin area are at the lower plains level, the net evapotranspiration may be so high during the summer months that streamflow is often reduced to zero before the end of summer. Groundwater discharge or baseflow recession constitutes the major source of streamflow along the later portion of the recession limb of the discharge hydrograph. In the absence of other significant sources, streamflow gradually approaches zero as the actual groundwater discharge approaches the

potential amount.

In most basins of the study area, almost all of the potential groundwater discharge is depleted during the summer. Groundwater recharge has to take place some time between then and the beginning of the baseflow recession in the following year. This period of recharge coincides largely with the winter season and early spring. Since most of the precipitation during this period is in the form of snow, any significant recharge has to take place during spring snowmelt and after the melting of ground frost. Recharge from summer rain is usually not significant because of the high evapotranspiration rates. Even when significant recharge does take place at times, the likelihood is that the water will be discharged and evaporated before winter begins.

Meyboom developed a method of hydrograph analysis based on Butler's equation. (Meyboom, 1961b, & Butler, 1957). The interested reader is referred to the original sources for details of the method. It suffices here to give a brief description of the procedure. The method involves the plotting of the discharge values from a particular basin against time on a semilogarithmic graph paper, with the assumption that the straight line connecting successive minimum points on the discharge hydrograph thus produced, approaches true baseflow conditions. Using Butler's equation, the total potential discharge at the beginning of the baseflow recession and the actual

discharge of groundwater are calculated. (Butler, 1957, p. 217).

The difference between the potential and actual discharge is called the remaining potential groundwater discharge at the end of the baseflow recession period, and the difference between this remaining potential groundwater discharge and the total potential groundwater discharge of the following year constitutes the groundwater recharge. Meyboom applied this method to the Elbow River Basin near Calgary (Meyboom, 1961a). He concluded from the analysis that the net recharge of groundwater within the basin over a period of years is negligible. Similar results are found in the study area.

The result of the computation of the groundwater balance for the Lodge Creek basin in Alberta based on the above method, is illustrated in Table 2.1. Since Lodge Creek is not a perennial stream like the Elbow River, some modification of the Meyboom technique is necessary. A discharge value of 0.1 c.f.s. is considered as the minimum value because one cannot plot zero values on a logarithmic scale. This is probably the reason that non-zero remaining potential groundwater discharge values exist even when it is obvious from the discharge records that the actual groundwater discharge has reached its potential amount. Hence, the values indicated are only approximations, but they show the nature of the groundwater balance as well as the order of magnitude of its various components and are therefore worthwhile presenting. It may be argued that the hydrograph

TABLE 2.1

LODGE CREEK AT ALBERTA BOUNDARY

GROUNDWATER BALANCE

1968 - 1972

Duration of Recession	Total Potential Groundwater Discharge (Acre-ft.)	Actual Groundwater Discharge (Acre-ft.)	Remaining Potential Groundwater Discharge (Acre-ft.)	Total Recharge (Acre-ft.)	Total Discharge (Acre-ft.)
	for the period shown				
June 16, 1967			.26		
March 16, 1968	383.00			392.74	2.88
July 2, 1968		389.86	3.14		
April 30, 1969	264.00			260.86	-0.5
June 5, 1969		261.36	2.64		
May 1, 1970	106.00			103.36	1.07
July 24, 1970		150.43	.57		
May 31, 1971	12.65			12.08	1.7
July 2, 1971		10.38	1.27		
April 1, 1972	161.00			159.73	.87
May 17, 1972		160.60	.4		
		927.63		928.77	6.02

Total Basin Area = 218,880 acres

Mean Discharge = 185.53 acre-ft. = 0.01 inch

Mean Recharge = 185.75 acre-ft. = 0.01 inch

$$\text{Recharge} = \text{Discharge} \pm \Delta\ \text{Storage}$$

$$0.01 = 0.01 \pm 0.0$$

relative minima do not provide good estimates to baseflow conditions. But even without computation using the Meyboom method, the fact that most streams of the study area dry up completely in late summer is a strong indication of insignificant net recharge in any one year.

It is obvious from the foregoing discussion that, so long as the actual groundwater discharge approximates the potential amount and the remaining potential discharge tends to zero or insignificant values, the groundwater recharge for any basin in any one year has to approximate the total groundwater discharge. It has already been noted that the major groundwater recharge in the study area occurs during spring snowmelt and most creeks dry up in late summer. It follows that for any particular year, most basins within the study area would have groundwater recharge equal to groundwater discharge, and the total quantity of streamflow for each of these basins is a function of the meteorological controls only.

2.8 The Measurement of Meteorological Conditions

2.8.1 The Meteorological Stations

Meteorological observations were taken from eight sites within the study area for the period June 1967 to September 1972. These sites were originally set up for studying the effects of topography on the atmospheric boundary layer. (Holmes, 1969, p. 5). The locations of the meteorological

stations are shown in Map 2.4. It is doubtful that these sites "would be representative of major kinds of terrains encountered in the Cypress Hills and vicinity" as Holmes claims. (Holmes, 1969, p. 5). It is also readily seen that the locations chosen are not ideal for hydrological investigations. For example, station density is far too low on the plains. Some of the basins chosen for the present study are left without a single meteorological station within the catchment area. Nevertheless, the records from these eight stations are the only significant sources of meteorological information upon which the present investigations must rely. Within the study area, there are also several climatological stations with discontinuous records of precipitation and temperature. In many cases, the amount of missing data from these climatological stations is large. Hence they are of little practical value for the purpose of the present study.

For convenience in later references, it is desirable to number these stations. The present numbering system follows that originally used by Holmes. (Holmes, 1969, p. 12). The following is a brief description of each observational site :

(1) Summit Bench Mark 4725 feet a.s.l.
latitude: 49° 37' 45" north
longitude: 110° 16' 15" west.

This site occupies a central position within the study area and is located on the crest of the plateau. It is about 82 feet lower than the highest point in the Cypress Hills

plateau and it has good exposure in all directions.

(2) Summit Forest 4760 feet a.s.l.
latitude: 49° 38' 0" north
longitude: 110° 17' 40" west

This site was set up to measure summit climatic conditions under forest. Because of its close proximity to Station 1 (Summit Bench Mark), its records are used as supplementary information to that of Station 1 for the purpose of the present study.

(3) West Summit plateau 4780 feet a.s.l.
latitude: 49° 37' 15" north
longitude: 110° 22' 20" west

This site is about 27 feet lower than the highest point on the Cypress Hills plateau. It was originally set up to measure the east-west variations of climate along the top of the plateau. Since the horizontal variation of climate along the plateau crest is not of prime importance to the present study, the record from this site is again used as supplementary information to that from Station 1. Together with Stations 1 and 2, it provides a reasonably good record of the crest level meteorological conditions.

(4) West plateau slope 4530 feet
latitude: 49° 36' 45" north
longitude: 110° 23' 10" west

This site is about 277 feet downslope from the highest point of the Cypress Hills, on the western extremity of the plateau. It is located on the west-facing slope and was originally set up to provide a transitional measure from crest to valley areas and for studying air drainage. It is still a transitional station for the purpose of the present study and due to insufficient stations at this elevation, the meteorological record from this station is used in interpolating values for the other slopes.

(5) North Slope Forest 4125 feet a.s.l.
latitude: 49° 37' 35" north
longitude: 110° 22' 45" west

Originally set up to measure the meteorological conditions of north forested slopes, it is now used as a transitional station between Station 4 and the open valley station below.

(6) Open Valley 3680 feet a.s.l.
latitude: 49° 37' 30" north
longitude: 110° 26' 10" west

This site is claimed by Holmes to be representative of valley and river-bed conditions. Situated on the western edge of the Medicine Lodge Coulee, this is one of the few low level stations within the area. It is only a couple of miles from the Eagle Butte climatological station at 49°33'N and 110°26'W, and at an elevation of 3700 feet a.s.l.

(7) North Prairie 3475 feet a.s.l.
latitude: 49° 45' 00" north
longitude: 110° 34' 20" west

This site was set up to represent the plains area north of the Cypress Hills plateau. It is situated between the plateau and Medicine Hat, and has the important role of being the only station for over 400 square miles of low level catchment area in the northern plains. Its importance is somewhat diminished by its peripheral rather than central position within the basin limits of the Ross Creek gauge near Irvine.

(8) South Prairie 3780 feet
latitude: 49° 27' 00" north
longitude: 110° 15' 00" west

This station was set up to represent the general conditions of the southern plains region. It is a well exposed site, situating between the Cypress Hills plateau and the meteorological station of Manyberries CDA. Its importance is again being the only station with significant record for over 550 square miles of low level catchment area. Discontinuous precipitation and temperature records may be obtained for several climatological stations, but the South Prairie site is still the major source.

Besides these eight meteorological sites in the Cypress Hills area and its vicinity, continuous meteorological records

for an extended period are obtainable from Medicine Hat and Manyberries CDA. These are two major stations in southeastern Alberta, one lying to the northwest and the other to the southwest of the study area. These are plains stations at 2180 feet a.s.l. and 3065 feet a.s.l. respectively.

2.8.2 The Meteorological Data

Meteorological Stations 1, 6, 7 and 8 are heavily instrumented stations while stations 2, 3, 4 and 5 are not. The kinds of instruments for each station are listed in Table 2.2. Daily observations were carried out during summer and weekly observations during winter from June 1967 to September 1972. The period of observation dictates the study period which is the five hydrological years beginning October 1967.

It is unfortunate that this equipment was not fully operated during the period of observation, and that considerable difficulties in measurement were encountered in winters. With regard to the problem in winter observation, Holmes wrote:

> "Frequently conditions become very bitter during winter months, with much snow, blowing and drifting snow, and low cloud. Clogging the Stevenson Screens with fine snow is frequent with stoppage of the clocks and v-lever linkages on the hygrothermographs. The hair of the hygrometer becomes coated with snow or frost with a subsequent continual indication of 100% relative humidity."
>
> (Holmes, 1969, p. 7)

TABLE 2.2

INSTRUMENTATION AT 8 SITES IN THE CYPRESS HILLS AREA

(After Holmes, 1969)

Observation	Station Number							
	1	2	3	4	5	6	7	8
Daily Maximum Temperature (1)	X	X	X	X	X	X	X	X
Daily Minimum Temperature (1)	X	X	X	X	X	X	X	X
Grass Minimum Temperature	X	X	X	X	X	X	X	X
Standard Rain Gauge (4)	X	X	X	X	X	X	X	X
Tipping Bucket Rain Gauge	X					X	X	X
Totalizing Anemometer (2) (4)	X	X	X	X	X	X	X	X
Anemograph (wind speed & direction) (3)	X						X	X
Hygrothermograph (1)	X	X	X	X	X	X	X	X
Sling Psychrometer (4)	X	X	X	X	X	X	X	X
Black Porous Disc Atmometer (4) (9)	X				X	X	X	X
Class "A" Evaporation Pan (4) (5)	X					X	X	X
Soil Temperature (4 & 8 inch "L" thermometer) (6)	X	X	X	X	X	X	X	X
Soil Temperature (7)	X							
Snow Fall (8)	X						X	X

(1) Screen height 1 ½ meters
(2) 2 Meters
(3) 10 Meters
(4) Observed at 0800 and 1700 hrs.
(5) Complete with water temperature and anemometer at pan rim height.
(6) Observed at 0800 and 1700 hrs.
(7) 5 cm, 10 cm, 20 cm, 50 cm, 150 cm and 300 cm observed at 0800 & 1700 hrs.
(8) Sacremento gauge and Knipfer shield, 3 Meters
(9) 1 ½ Meters

Consequently, a considerable quantity of data is missing. The data available are not ideal for the purpose of hydrological studies. To estimate spring snowmelt runoff, winter precipitation data are essential. Winter precipitation records at the eight stations are insufficiently recorded at best, and non-existent at worst. Under such conditions, one cannot start with any investigation of relationships until the winter precipitation has been estimated. Fairly regular records of snow on ground are available for the winters. However, difficulty arises as one tries to use the snow on ground data, for there were no snow course surveys at the eight meteorological sites, which means that the snowpack density and hence the water equivalent of the snowpack at the stations is unknown. The only snow course in operation within the area is the one at Elkwater, at the northern foothills of the Cypress Hills plateau. Here at Elkwater, the snow density variation during the five spring seasons from 1968 to 1972 is as follows:

Year	Snow density on March 1st
1968	.4
1969	.2
1970	.29
1971	.23
1972	.167

There is considerable variation from year to year, and it is also likely that considerable spatial variation exists. Hence it would be meaningless to estimate an average snow density value, and consequently the snow on ground data can only be used as rough indices in some procedures of winter precipitation estimation.

The temperature data are comparatively good. For the purpose of the present study, the temperature data may be used to represent potential evapotranspiration, air humidity and perhaps soil moisture conditions.

The observations from a meteorological station show only the atmospheric conditions at a point. It is necessary to estimate the conditions for the entire drainage basin using these point estimates. Areal estimates of the meteorological parameters are obtainable from the point estimates by various methods.

2.9 The Measurement of Hydrological Conditions

2.9.1 The Hydrometric Stations: River Discharge Gauges

As the period of meteorological observation dictates the length of the study period, the selection of hydrometric stations dictates the size of the study area. There are eight hydrometric stations selected, covering a total catchment area of over 1250 square miles. Each one of these is essentially the first gauge downstream from the Cypress Hills plateau. It is again convenient to number the gauges for easy reference later. The locations, drainage areas and numbers are indicated in Table 2.3. The watershed shapes and gauge locations are shown in Figure 2.7.

It should be noted that Gauge 2 and Gauge 7 (Gros Ventre

TABLE 2.3

THE HYDROMETRIC STATIONS

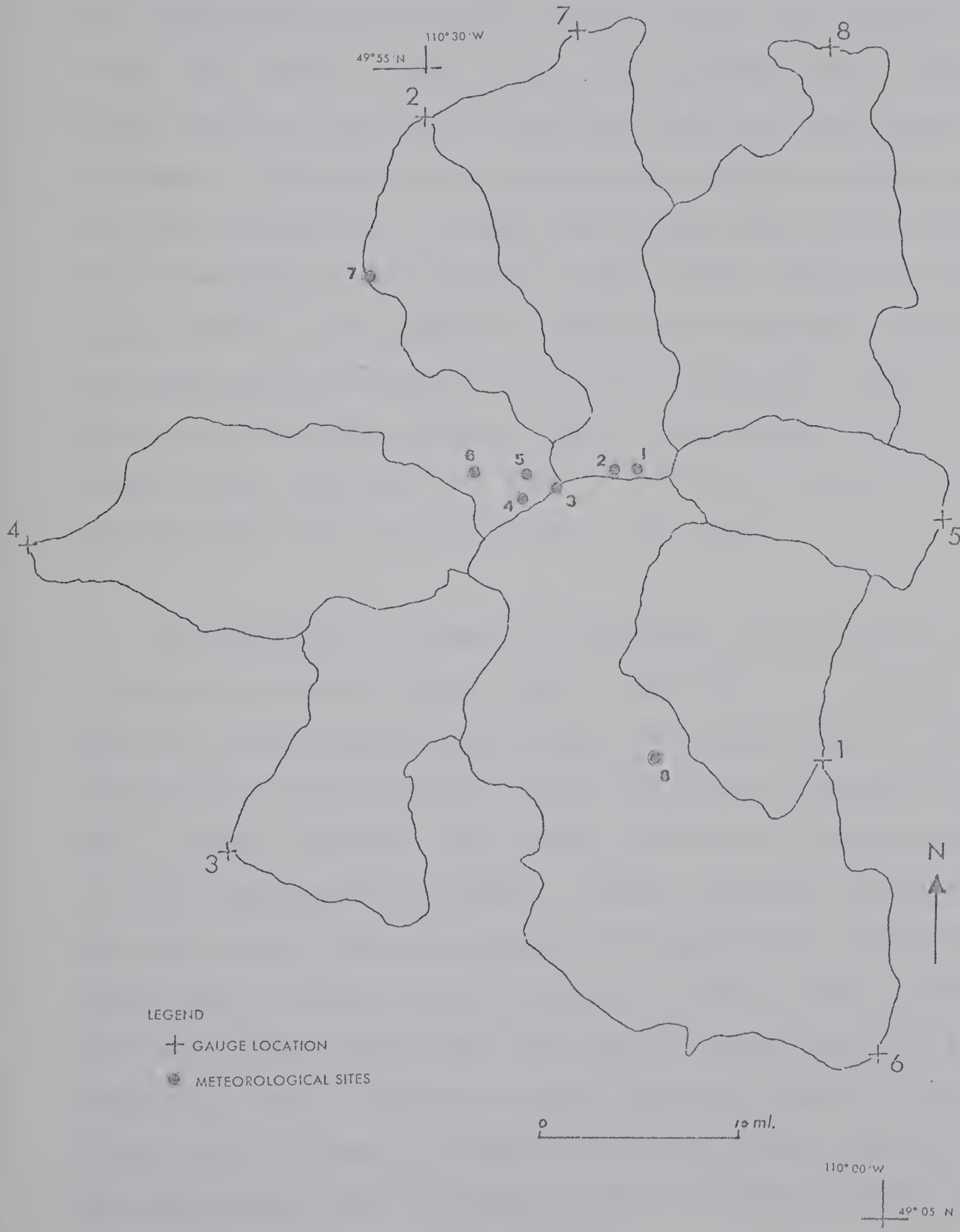
POSITION, DRAINAGE AREA AND NATURE OF FLOW

Station No.	Station Description	Latitude (North)	Longitude (West)	Nature of flow	Drainage area (sq. ml.)
11AB009 (1)	Middle Creek near Alberta boundary	$49^{0}25'29''$	$110^{0}3'9''$	Natural	116
05AH037 (2)	Gros Ventre Creek near Dunmore	$49^{0}53'20''$	$110^{0}30'20''$	Natural	82
05AH010 (3)	Manyberries Creek at Brodin's Farm	$49^{0}21'30''$	$110^{0}43'30''$	Natural	137
05AH041 (4)	Peigan Creek near Pakowki Road	$49^{0}34'50''$	$110^{0}56'30''$	Natural	163
11AB081 (5)	Battle Creek at Ranger Station	$49^{0}36'4''$	$109^{0}55'21''$	Natural	75
11AB082 (6)	Lodge Creek at Alta. Boundary	$49^{0}12'50''$	$109^{0}59'40''$	Natural	342
05AH003 (7)	Ross Creek near Irvine	$49^{0}57'17''$	$110^{0}20'8''$	Regulated	234
05AH002 (8)	Mackay Creek at Walsh	$49^{0}56'30''$	$110^{0}2'40''$	Regulated	200

NOTE: Gauge Number in brackets.

FIGURE 2:7

BASIN DELIMITATION WITH LOCATION OF STATIONS



Creek near Dunmore and Ross Creek near Irvine respectively) are nested basins. While Gauge 7 has regulated flow, natural flow is maintained at Gauge 2. (Gros Ventre Creek flows into Ross Creek and Gauge 7 or Ross Creek is below the junction of the two streams. As a result, the drainage area of Gros Ventre Creek is also part of the Ross Creek drainage basin at Gauge 7. The Gros Ventre Creek basin is hence nested within the Ross Creek basin. A significant point about nested basins is that watershed characteristics for various portions of the larger basin can be examined. Downstream discharge can also be predicted from records of the upstream gauges, and by comparing the streamflow records from various gauges within the larger basin, the basin lag time for different portions of the drainage area can be accurately assessed).

The selection of gauges is completely limited by the distribution of meteorological sites. The choice of a larger basin by using a gauge further downstream would mean a further reduction of meteorological station density by increasing the area covered. However, the present selection of gauges forms a fairly representative sample. Streams flowing into each of the three major drainage systems are represented. Basin sizes range from 75 square miles for Gauge 5 (Battle Creek at Ranger Station) to 342 square miles for Gauge 6 (Lodge Creek at Alberta boundary). Basin elevation ranges from the essentially low level basin of Gauge 4 (Peigan Creek near Pakowki Road) to the crest level basin of Gauge 5 (Battle Creek at Ranger Station).

Gauges 2, 7, and 8 are on the north-facing slope, while Gauges 1,3, and 6 are on the slope facing south.

2.9.2 The Hydrometric Data

The major information required is the discharge record . All of the gauges have a longer period of record than the meteorological stations. Day to day discharge records are available for all eight gauges and this makes the plotting of detailed hydrographs possible. Streamflow characteristics represented by the discharge records are the total discharge, the peak discharge and the time of occurrence of peak discharge, the relationships of which to the meteorological variables are to be investigated.

The locations of the gauges are of a considerable distance downstream from most meteorological sites which occupy upstream locations. The absence of any upstream gauges means that many of the immediate responses of streamflow to the meteorological changes as observed at the meteorological stations may not be easily detected. Streamflow data from upstream gauges are desirable for the purpose of the present study. Nevertheless, the discharge measured at a gauge is an areal estimate representing the net water surplus from the entire basin area, and the selected gauges are the most up tream ones available, and for significant events like spring flooding, it is expected that some detectable relationship exists between the upstream observed weather and the downstream measured runoff.

CHAPTER III

RESEARCH METHODOLOGY

> When you can measure what you are speaking about and express it in numbers, you know something about it. But when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager unsatisfacory kind.
>
> - Lord Kelvin

3.1 Introduction

In this chapter, the methods used in examining the meteorological-hydrological relationships and model formulation are described. The aim is to provide quantitative assessments of the relationships. It is felt that such assessments will provide a better picture of the situation, through not necessarily because of what Lord Kelvin said. The 1957 Thornthwaite Water Balance procedure is used in the computation of runoff and in the determination of the water balance zonation within the study area. Isoline maps are produced to illustrate the runoff patterns. Linear multiple regression analyses are used in the investigation of the nature of relationships between the hydrological and meteorological variables and in the development of prediction models. The goals of model formulation are stated. The pertinent literature is reviewed.

3.2 The Water Balance

In the present study, it is the monthly water balance which will be computed. The climatic water balance can be represented by the equation:

$$Ppt = (PE - D) + Sur \pm \Delta St$$

Where Ppt = precipitation

PE = potential evapotranspiration

D = deficit

Sur = surplus

ΔSt = storage change

Precipitation is a frequently measured meteorological parameter, the records of which are available for most meteorological stations. It includes values of all forms of precipitation in terms of water equivalent. The storage change term represents changes in soil moisture storage, the range of which is from wilting point to pore saturation for root depth. Storage change may be positive or negative. If a positive change gives an above-capacity value, the excessive water is entered as surplus. Surplus is the total quantity of water that is subject to runoff. It exists only after the soil moisture storage has reached the water holding capacity. Normally, it is only a portion of the surplus water that is available for runoff in a particular month. The rest is largely detained in groundwater storage until later months. Deficit represents the difference between potential and actual evapotranspiration. Therefore, the term in brackets (PE - D) represents the actual evapotranspiration amount. Potential evapotranspiration is a quantity to be estimated, using the temperature data, latitude of the meteorological station, and the available empirical tables or a computing program

written for the same purpose. It is worthwhile mentioning that the water balance equation in this form is a concise, numerical expression of the meteorological-hydrological relationship at a point.

3.2.1 The Thornthwaite Method of Potential Evapotranspiration Estimation.

Potential evapotranspiration was defined as "the amount of water which will be lost from a surface completely covered with vegetation if there is sufficient water in the soil at all times for the use of the vegetation". (Thornthwaite and Mather, 1955, p. 15). From the hydrological cycle point of view, potential evapotranspiration represents the maximum quantity of water transportable from earth to atmosphere under the prevailing meteorological conditions, assuming unlimited water supply. It is an index of water need which exists theoretically, but in practice, is difficult to measure. When it is compared with precipitation, (P - PE), a "rational definition of the moisture factor" as Thornthwaite called it, can be obtained. It is on the basis of this moisture factor and the potential evapotranspiration concept that Thornthwaite advanced his famous 1948 climatic classification. There are several approaches to the estimation of potential evapotranspiration. A number of procedures, eg. Penman, Turc, Lowry and Johnson, Blaney and Criddle, Hargre ve, Mohrman and Kessler, Budyko, etc., had been tested and it was concluded that the Thornthwaite procedure was the most appropriate water balance computation method for the prairies. (Laycock, 1970 and Laycock,

1967). Thornthwaite's method of potential evapotranspiration estimation can be expressed by an empirical formula relating potential evapotranspiration to temperature and daylength. (Thornthwaite, 1948 p. 89 - 90) Computation may be carried out using either empirical formulae or the tables published for such purposes. (Thornthwaite and Mather, 1957)

Imperfection in such an approach is inevitable, e.g. the sole dependence on temperature value and the assumption of no evapotranspiration below 30.2°F (-1°C). However, it is argued that other factors affecting evapotranspiration, such as wind, humidity and solar radiation, would vary together with temperature (Thornthwaite and Mather, 1955, p. 15), and that underestimated potential evapotranspiration may be partially compensated for by the under measurement of snowfall and non-measurement of condensation on surfaces of snow. (Laycock, 1973, p. 86)

The method is widely used because of its simple requirements and straight forward computation procedure. Considerable success has been reported. For example, Carter's 1955 study of the water balance of the Lake Maracaibo Basin, and Sanderson's 1966 study of the water balance of the Lake Erie Basin are among the widely cited ones. (Carter, 1955 and Sanderson, 1966). It is used in the present study because of the possibility of using the potential evapotranspiration estimates later in the computation of water balance for the basins. It is also because of the fact that there are not enough data available for the use of

more elaborate techniques of potential evapotranspiration estimation; the Thornthwaite method is the most appropriate choice.

3.2.2 The Thornthwaite Method of Water Balance Computation

This is a bookkeeping method of water balance computation, starting from the computation of potential evapotranspiration as mentioned in the previous section, through steps of moisture factor calculation, soil moisture storage and surplus calculation and eventually runoff calculation. The detailed procedure as used in the present study is described in Thornthwaite and Mather's 1957 publication. (Thornthwaite and Mather, 1957, p. 185 - 203). A computer program is available following this procedure. It is a modification of the Silviculture General Utility Library Program GU-101, written by P. E. Black of Syracuse University, Syracuse, New York in 1966.

The use of Thornthwaite's climatic water balance in the present study is more than a mere sequence to the use of the Thornthwaite method for potential evapotranspiration estimation. The Thornthwaite climatic water balance procedure is the best available method that takes into consideration winter precipitation values. Since the present study is concerned with spring snowmelt runoff, which depends heavily on the amount of winter precipitation, the Thornthwaite computation procedure becomes the best choice for estimating runoff.

The result of computation using the Thornthwaite technique includes, in addition to runoff, values of the other components of the water balance equation. Focus may thus be placed upon the potential evapotranspiration or actual evapotranspiration, or changes in the soil moisture stored. Maps showing the spatial patterns of various elements in the water balance equation can also be constructed.

3.2.3 Literature Review

The use of Thornthwaite's climatic water balance in computing runoff has been carried out by various researchers. Thornthwaite and Mather mentioned several studies involving various basin sizes and different climatic zones, and in each case, the estimated runoff was in close agreement with the observed values. (Thornthwaite and Mather, 1955, p. 48 - 55). These basins include tributary watersheds of the Muskingum Drainage Basin in Ohio, the Tennessee River Basin, the James River Basin in Virginia and the Lake Maracaibo Basin in Venezuela. In the Canadian scene, similar results have been obtained recently by Sanderson, who used computed water surplus figures of 1959 - 1960, to produce a map of water surplus for the Grand River Basin. She found a correlation coefficient of 0.995 when she correlated the computed runoff of some fifteen basins with the measured runoff. She concluded that the Thornthwaite procedure provided good estimates of runoff and ".......an excellent correlation was obtained in spite of the varied glacial topography and soils in the area

......" (Sanderson, 1966, p. 17).

Sanderson and Phillips studied the average annual water surplus pattern in Canada, and by using the Thornthwaite method of runoff calculation, they were able to produce maps of runoff which "agreed very well along the southern border of Canada with Langbein's map of (measured) runoff in the United States". (Sanderson and Phillips, 1967, p. 27). In the same study, references were also made to several unpublished theses, which had found high correlation coefficients between the measured and computed values of actual evapotranspiration as well as runoff. (Ibid, p. 2).

Kakela investigated the applicability of the Thornthwaite procedure in a subarctic environment. (Kakela, 1969). Although a statistically insignificant correlation coefficient suggested that the measured and computed runoff in a subarctic basin do not vary in the same manner, the twenty-five year mean values of these two variables were "reasonably close". (Kakela, 1969, p. 215). For the Canadian prairies, Laycock used the Thornthwaite procedure and produced a series of maps showing water surplus and deficiency patterns. (Laycock, 1967). In an unpublished M.Sc. Thesis, Erxleben applied the Thornthwaite technique of runoff estimation to the Whitemud Creek Basin and concluded that it is "reasonably suitable for water balance calculation for the Edmonton region". (Erxleben, 1972). In the light of these results, the author

believes that the Thornthwaite Water Balance computation is the most suitable, if not ideal, procedure to be employed in the present study.

3.3 The Isopleth Mapping Method

Isopleth mapping is used in the description of the pattern of runoff in the study area. It is a conversion of the point measures at the meteorological stations to the area measures of the drainage basin as a whole. Adjustments may be made according to the physical characteristics of the basin area so that a more realistic distribution pattern can be described. Subjective judgement is involved where station density is not high enough to provide adequate information, and the accuracy of the distribution pattern depends heavily on the skill and experience of the person who draws the map. Nevertheless, this is the most suitable method for the present study, where considerable interpolation is required, and where topographic influence on climate plays a significant role.

3.3.1 Mapping Procedure

The procedure of isopleth mapping in the present study includes three major steps: (1) The delimitation of basin areas, (2) The drawing of the isopleths and (3) The comparison between measured and computed runoff.

(1) The delimitation of the basin area: The sizes of drainage basins in the prairies tend to vary from year to

year because of the special surface characteristics of glaciated terrain. There is considerable surface storage due to the presence of numerous sloughs, which have their individual small catchment areas. In a dry year, surface runoff is often retained in these sloughs and consequently is not available for discharge in the streams. As a result, the effective drainage area of a prairie basin tends to be smaller, and the flood peak for the entire basin is much reduced. Conversely, a wet year will cause the interconnection of these sloughs by temporary water-channels, and water from their individual small catchment areas may contribute to the discharge of the main streams. The effective catchment area of the main basin as well as the flood peak is thus increased. This is still an unsolved problem in basin delimitation in the prairie. (Gray, 1964, p. 159).

For the purpose of the present study, it is fully recognized that the inevitable inclusion of such surface depressional storage areas will cause inaccuracy in the estimation of actual runoff. No matter what the moisture condition of a particular year is, the presence of sloughs will always lead to an overestimation of the actual runoff by the climatic water balance. A quantity of the available runoff is always retained by the depressions. Thus even when the effective catchment area is increased in a wet year, the total effective catchment area can never be equal to the actual area as delimited by the major divides. It is expected that such overestimation of runoff can be partly compensa-

ted by the underestimation of winter precipitation as mentioned in the Appendix of this study. Furthermore, judging from the topography and overall climatic conditions of the study area, it is likely that the surplus areas will have comparatively little overlapping with the lower level rolling plains, where most of the sloughs are found. Finally, it is difficult to assess quantitatively the effect of the variability of the effective catchment area on total runoff. One does not know how wet a wet year has to be in order to cause significant changes in effective catchment area and total discharge. At Medicine Hat, the precipitation of the wettest year during the study period is only 12% above the five year mean from 1967 - 1972. It is perhaps not unreasonable to assume, for the purpose of the present study, that the errors in runoff estimation due to surface slough storage are negligible. Moreover, groundwater yield from these enclosed basins especially those in the higher and coarser textured morainic areas also tend to make runoff variation due to this factor insignificant in most if not all years.

It is thus assumed that the basin area bounded by the major topographical divides approximates the effective catchment area. The areas of the basins are measured by a planimeter, and comparison is made with the areas measured by the Water Survey of Canada to ensure reasonable accuracy.

(2) The drawing of the isopleths: Topographic influ-

ence is the most important environmental factor to be considered in the production of hydroclimatic maps for the study area. Contour maps are used as base maps for the drawing of runoff isopleths. The maps used are the National Topographic Series 1:250,000 sheets 72E and 72F. An isopleth map is produced for each of the five years of the study period. The actual procedure is as follows:

An overlay map was prepared showing the basin delimitations. The actual locations of the meteorological stations were accurately plotted. The runoff values at the stations for the particular year were indicated. Then the isopleths were sketched in. The orientation and spacing of the isopleths are adjusted according to considerations of topography, water balance characteristics and other climatic influences such as chinook frequencies and direction of the average storm track. Vegetation distributions would be used later to evaluate the adequacy of the first sketch.

The accuracy of the isopleths drawn depends upon the number of point values available. The greater the number of points, the smaller the interpolation will be, and consequently the more objective the results become.

(3) The comparison between measured runoff and computed runoff: This serves as a final check on the runoff pattern obtained from the previous procedures. Areas between succ-

essive isopleths were planimetered and then multiplied by the average depth of annual runoff. The volume of runoff thus produced was converted to depth of runoff for the entire basin. This was then compared with runoff values measured at the hydrometric station at the outlet of the drainage basin. It is fully realized that agreement between measured and computed runoff does not guarantee the complete accuracy of the computed runoff pattern. Various distributions of surplus areas can produce the same quantity of aggregate basin runoff. However, this does serve the useful purpose of a final check, while the determination of the general surplus pattern within the basin depends heavily on the interpretation of topographic influence carried out in the previous step.

3.3.2 Literature Review

Isopleth-mapping is a common cartographic technique in describing the spatial distribution of a geographic variable. Although this is widely used, there are comparatively few studies done regarding the actual application problems. One of the earlier reports was written by Mackay who discussed the problems and techniques of isopleth-mapping. (Mackay, 1951). Carter, who has carried out water balance studies in various areas outside North America, stressed the importance of topographic influence on the mapping of hydroclimatic parameters.

"Topographic diversity is reflected in nearly all

> climatic distributions, consequently, the topographic map is to some degree a guide to interpolation among climatic values. For example, elevation is usually correlated with lower potential evapotranspiration, with smaller water deficit and greater water surplus and precipitation."
>
> (Carter, 1954, p. 453).

He also suggested that oceanic influence is to be considered for the mapping of coastal areas, and that vegetation and soil maps are to be used to evaluate the adequacy of the isopleth pattern.

In Canada, nation-wide surplus patterns were described by Sanderson using the isopleth-mapping method. (Sanderson, 1967). She also did several studies on the water balance pattern of Eastern Canada and hydroclimatic isopleth maps were produced. (Sanderson, 1966 and Sanderson, 1971). In her 1966 study of the Lake Erie Basin, precipitation values at perimeter stations were used to produce isohyetal maps for the area over the lake. She then concluded that "the isopleth mapping method of estimating over water precipitation for the specific monthly conditions.........might result in smaller monthly errors than using empirical corrections". (Sanderson, 1966, p. 31). In her 1967 study, average surplus maps were produced using topographic maps as base maps. Some aspects of the application of hydroclimatic isopleth-mapping were discussed. It was found necessary to use different scales for different parts of Canada. The isopleth intervals used also depended on the area shown. A geometric scale of isopleth intervals was used for Central and Western

Canada where variation of surplus was great. The average water surplus values for each province were then computed from the isopleth patterns. (Sanderson, 1967, p. 3 - 4).

3.4 Regression Analysis

Regression analysis is an often-used statistical technique in providing approximations to complex functional relationships in a physical system. The approximations may be expressed as simple mathematic equations, such as a polynomial. The hydrological system is a complex physical system involving many variables. The relationships among these variables are often studied, but the underlying principles are poorly known. Regression Analysis is commonly used in hydrological studies. It is one of the few numerical methods which can be used to evaluate simultaneously the effects of several causative factors. The regression model may be unrealistic physically, but for the hydrologist, who is working with uncontrolled experiments essentially, regression analysis is a useful tool. Yevjevich broadly categorizes the current use of regression in hydrological studies into two major types:

(a) For the investigation of cause-effect based relations, where a dependent random variable Y is related to an independent random variable X (or a group of independent variables X_1, X_2, ...X_N). The independent variable (or independent variables) can produce or affect the outcome of the dependent variable Y.

(b) For the investigation of relations of random variables, which have the same causative factor e.g. the correlative association of the runoff of a stream to the runoff of the adjacent streams.

(Yevjevich, 1972a, p. 233)

The present study involves the application of the multiple linear regression technique in a hydrometeorological approach to stream discharge forecasting. Streamflow characteristics are related to meteorological factors in the regression analysis. The results of the climatic water balance computations can be used as guidelines in variable selection. It is the investigation of cause-effect based relationships with prediction as the ultimate goal. The predictors are the meteorological variables and the predictands represent various characteristics of streamflow.

3.4.1 The Often-violated Assumptions

There are two often violated basic assumptions in a multiple linear regression analysis:

(1) It is assumed that for each selected independent variable X, there is a normal distribution of the dependent variable Y from which the sample value of Y is drawn at random.

This assumption is important when statistical significance tests are involved. Many of these tests are based on the Gaussian normal distribution of events. Hydrometeoro-

logical data are often found to be non-normally distributed They may be severely skewed because of the relatively small number of great events and large number of small events. Transformation to normal distribution is usually carried out if statistical significance tests are to be applied.

(2) Independence among the predictors:

This is required for the stability of the regression model. The lack of independence means that the addition or subtraction of a predictor would cause changes of the values of the regression coefficients and the relationship indicated by the regression model would not be stable. However, for the purpose of prediction alone, the lack of independence does not lead to invalidation of the regression model. In such cases, the same interdependence is assumed to exist all the time (Matalas & Reiher, 1967, p. 213). When regression technique is applied to hydrometeorological studies, the independence assumption is often violated because of the intercorrelation among hydrometeorological variables. Orthogonalization techniques such as principal components anaylsis are often used to ensure independence.

3.4.2 Literature Review

MuCulloch and Booth used the Thiessen polygon method to estimate the aggregate basin precipitation, and regression analysis was then applied to relate the aggregate basin precipitation to the individual station precipitation values.

Using only four to five stations as predictors, they were able to obtain successful results. (McCulloch and Booth, 1970, p. 1755). Williams used regression analysis to predict lake ice breakup dates. The independent variables used were past breakup dates and air temperature records. (Williams, 1971, p. 323).

One of the pioneers in using regression anaylsis in discharge forecasting is Wong. In his 1963 study of the New England area, he found that orthogonalization by principal components technique was necessary in order to produce successful results by regression. (Wong, 1963). Similar conclusions were reached by Spence who studied the streamflow characteristics of the Canadian prairies. (Spence, 1971). However, in Wong's study, only one variable was selected as a surrogate for each principal component identified from the principal components technique. In this way a more interpretable model was obtained, which was also easier to reapply. Here, the principal components analysis was also a tool for variable selection. On the other hand, Mustonen found that normal regression is better than orthogonal regression. (Mustonen, 1967, p. 123). His regression equation was found to explain runoff very well, despite strong correlation among the independent variables. He also argued that independence was not necessary because it was "meaningless in such studies to identify the individual effects of the independent variables". (Mustonen, 1967, p. 123).

Lull and Sopper, in their 1966 paper entitled "Factors that influenced streamflow in the Northeast" reported that regression technique was used in relating average annual and seasonal discharge to selected climatic, topographic and land use variables. (Lull and Sopper, 1966, p. 371). They found that satisfactory results were obtained by using only three to five variables and that annual runoff correlated better with isohyetal precipitation than with station values. Regression technique was used by Schreiber and Kincaid in studying storm runoff in Southeastern Arizona. (Schreiber and Kincaid, 1967). The result showed that runoff was largely controlled by storm characteristics, and that antecedent soil moisture played only an insignificant role. This may be compared with the conclusion by Hartman et al that "the most important factor in runoff prediction is the amount of moisture in the top three feet of soil at the time rainfall begins". (Hartman, Baird, Pope and Knisel, 1960). The Schreiber and Kincaid study was followed and extended by Osborne and Lane. (Osborne and Lane, 1969). Discharge was found to have significant regression on precipitation values alone. Similar results were also reported by Baker, who found that the winter precipitation values at a single station was the significant predictor for spring runoff from the Cottonwood River Basin in Minnesota, even when the total watershed area was 1280 square miles. (Baker, 1972).

Different regression models have to be developed for different areas and there can be little transferability of prediction models. A most suitable subset of predictors will have to be chosen for each basin and for each predictand. There may also be times when the prediction models need to be updated. Nevertheless, regression analysis is the most suitable technique to be used in approximating the complex relationships amongst the hydrometeorological variables. It is also the major statistical technique in the present study for formulating prediction models of stream discharge.

3.5 The Goals of Modelling

> "Models can be viewed as selective approximations which by the elimination of incidental detail, allow some fundamental, relevant or interesting aspects of the real world to appear in some generalized form".
>
> (Chorley and Haggett, 1969, p. 23)

Models are links between observation and theory. They are condensed forms of relevant information about a certain phenomenon of the real world. In simple, intelligible terms they explain how the phenomenon comes about. On the other hand, they are selective approximations at best, and their reapplicability is restricted only to the range of conditions under which they are formulated. When they are used for predictive purposes, a probability of error always exists. The major task is then to develop a meaningful and

representative model and at the same time minimize the probable error when prediction is involved. It is necessary to state, at this stage, the goals of modelling for the present study: (1) Only theoretically relevant variables are to be used as predictors. i.e. The predictands should be theoretically related to the predictors selected. (2) A regression model with a 10% statistical significance level will be considered as acceptable. Significance level greater than 10% would mean a probability of making error so great that the model could have little practical value. It is also necessary to test for the applicability of the models. The existing data will have to be used because observations at the meteorological stations have been discontinued. The final year of record is to be set aside for testing purposes. The formulation of the regression models is based on the records of the first four years.

CHAPTER IV

THE WATER BALANCE

4.1 Introduction

The results of water balance computations for each meteorological station using the Thornthwaite 1957 procedure are presented, and the spatial patterns of water surplus for each year are mapped. A gradient pattern of moisture storage capacity was assumed in the water balance computation, and a gradient pattern of water surplus was assumed in the production of the surplus maps. It is believed that the patterns developed are the best approximations using the available information, although imperfection undoubtedly exists. Data deficiency and undesirable locations of meteorological stations are the major difficulties limiting further improvements of the present results.

4.2 The Thornthwaite Procedure

In the computation of water balance using the Thornthwaite 1957 procedure, a number of values of soil moisture storage capacity were involved. It was not feasible to measure this parameter at the meteorological stations for the present study. Hence, a number of estimated values for the soil moisture storage capacity were attempted. A soil moisture storage capacity of four inches was used for the lower level plains stations in the present study, and a soil moisture

storage capacity of six inches was used for stations at the plateau crest. It was assumed that a gradient pattern in storage capacity existed between the plains level and the higher crest level, and an intermediate capacity of five inches was used for the slope stations.

Laycock used a four inch soil moisture storage capacity for this part of the prairie provinces and Buckler used a value of three inches for the Pembina Basin and successful results were reported in both. (Laycock, 1973, p. 97, with recorded discussion with S.J. Buckler). The use of a six inch field capacity for the high level station was based upon the fact that loess soils in general have finer texture, and hence greater field capacity. Higher storage capacity is also due to the vegetation cover. Although it is a grassland type cover at the plateau crest, it is relatively luxuriant and is mixed with aspen, pine and other forest cover. Smaller values were used for the crest stations, but the resulting runoff from the water balance computation had higher values than were likely to have occurred. It is considered that the present values of soil moisture storage capacity for the various levels provide the most realistic results of water balance computation.

Also, in the computation of water balance, the calendar year was used instead of the hydrological year because of the more simplified calculation procedure involved in obtaining

various starting values such as the potential water loss carried over and the storage carried over values. Here, it was assumed that the total precipitation of the two months prior to the beginning of the period of water balance computation approximated the storage carried over for the initial year. This is valid because runoff in the late summer and fall months in the study area is usually low or even non-existent, and during November and December, evapotranspiration is low and precipitation essentially occurs in the form of snow which accumulates on the ground. By using the calendar year, it was also easier to obtain the potential water loss carried over value , (This is the value of potential water loss with which to start the accumulation of negative (P-PE) values. It is needed in stations where the annual sum of (P-PE) is negative.) because the months with negative moisture factor (P-PE) would occur together rather than separated into two periods, and in many cases, the potential water loss carried over value was found to approach zero.

The monthly water balance equations of the meteorological stations are shown in Table 4.1 to 4.10. The equations are in the form:

$$P_pt = (PE-D) \pm \Delta St. + Sur.$$

which represent respectively, precipitation, potential evapotranspiration, deficit, storage changes and surplus. The surplus term is of particular interest. For the purpose of the present study, the total monthly water surplus available

TABLE 4.1a

ANNUAL WATER BALANCE

STATION: MANYBERRIES CDA

SOIL MOISTURE STORAGE CAPACITY = 4 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1968

Jan 0.9 = (0.0 - 0.0) + 0.9 + 0.0
Feb 0.2 = (0.0 - 0.0) + 0.2 + 0.0
Mar 0.7 = (0.6 - 0.0) + 0.1 + 0.0
Apr 1.0 = (1.1 - 0.1) + 0.0 + 0.0
May 1.0 = (2.7 - 1.2) - 0.4 + 0.0
Jun 2.5 = (4.1 - 1.3) - 0.2 + 0.0
Jul 0.4 = (5.3 - 4.6) - 0.4 + 0.0
Aug 2.1 = (4.3 - 2.1) - 0.1 + 0.0
Sept 2.0 = (2.8 - 0.8) + 0.0 + 0.0
Oct 0.3 = (1.2 - 0.9) + 0.0 + 0.0
Nov 0.3 = (0.0 - 0.0) + 0.3 + 0.0
Dec 1.3 = (0.0 - 0.0) + 1.3 + 0.0

Yr 12.6 = (22.1-11.1) + 1.6 + 0.0

1969

Jan 2.4 = (0.0 - 0.0) + 2.4 + 0.1
Feb 0.8 = (0.0 - 0.0) + 0.0 + 0.8
Mar 0.2 = (0.0 - 0.0) + 0.0 + 0.2
Apr 0.7 = (1.8 - 0.1) - 1.0 + 0.0
May 0.3 = (3.2 - 1.4) - 1.6 + 0.0
Jun 1.9 = (4.0 - 1.5) - 0.6 + 0.0
Jul 1.1 = (5.1 - 3.5) - 0.5 + 0.0
Aug 0.4 = (5.2 - 4.6) - 0.2 + 0.0
Sept 0.4 = (3.1 - 2.6) - 0.0 + 0.0
Oct 1.1 = (0.3 - 0.0) + 0.9 + 0.0
Nov 0.0 = (0.1 - 0.0) + 0.0 + 0.0
Dec 0.2 = (0.0 - 0.0) + 0.2 + 0.0

Yr 9.7 = (22.8-13.8) - 0.5 + 1.2

*Computer rounding error may cause the equations to be out of balance by about 0.1 inch. Since this, in a way, indicates the magnitude of the values before rounding, it is the intention of the author to present them as they are.

*All units = inches.

TABLE 4.1b

ANNUAL WATER BALANCE

STATION: MANYBERRIES CDA

SOIL MOISTURE STORAGE CAPACITY = 4.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970

Jan	0.9 = (0.0 - 0.0) + 0.9 + 0.0
Feb	0.5 = (0.0 - 0.0) + 0.5 + 0.0
Mar	0.7 = (0.0 - 0.0) + 0.7 + 0.0
Apr	0.8 = (0.7 - 0.0) + 0.1 + 0.0
May	0.6 = (3.1 - 1.0) - 1.5 + 0.0
Jun	5.5 = (5.0 - 0.0) + 0.5 + 0.0
Jul	1.8 = (5.5 - 2.4) - 1.3 + 0.0
Aug	0.7 = (4.9 - 3.7) - 0.6 + 0.0
Sept	0.2 = (2.5 - 2.1) - 0.1 + 0.0
Oct	0.3 = (0.8 - 0.5) + 0.0 + 0.0
Nov	0.6 = (0.0 - 0.0) + 0.6 + 0.0
Dec	1.4 = (0.0 - 0.0) + 1.4 + 0.0
Yr	13.9 = (22.5- 9.7) + 1.1 + 0.0

1971

Jan	2.5 = (0.0 - 0.0) + 1.8 + 0.7
Feb	0.4 = (0.0 - 0.0) + 0.0 + 0.4
Mar	0.5 = (0.0 - 0.0) + 0.0 + 0.5
Apr	0.9 = (1.3 - 0.0) - 0.4 + 0.0
May	1.1 = (3.1 - 0.6) - 1.4 + 0.0
Jun	3.6 = (4.1 - 0.2) - 0.3 + 0.0
Jul	0.5 = (5.0 - 3.2) - 1.3 + 0.0
Aug	1.1 = (5.7 - 4.2) - 0.4 + 0.0
Sept	0.2 = (2.4 - 2.1) - 0.1 + 0.0
Oct	0.5 = (1.0 - 0.4) - 0.0 + 0.0
Nov	0.2 = (0.0 - 0.0) + 0.2 + 0.0
Dec	0.8 = (0.0 - 0.0) + 0.8 + 0.0
Yr	12.4 = (22.7-10.7) - 1.1 + 1.6

TABLE 4.2a

ANNUAL WATER BALANCE

STATION: MEDICINE HAT

SOIL MOISTURE STORAGE CAPACITY = 4.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1968	
Jan	0.3 = (0.0 - 0.0) + 0.3 + 0.0
Feb	0.2 = (0.0 - 0.0) + 0.2 + 0.0
Mar	0.3 = (0.8 - 0.5) - 0.1 + 0.0
Apr	1.7 = (1.2 - 0.0) + 0.5 + 0.0
May	1.4 = (3.0 - 1.3) - 0.3 + 0.0
Jun	4.2 = (4.3 - 0.1) - 0.0 + 0.0
Jul	0.9 = (5.3 - 4.0) - 0.4 + 0.0
Aug	0.5 = (4.4 - 3.7) - 0.1 + 0.0
Sept	2.4 = (3.0 - 0.6) - 0.0 + 0.0
Oct	0.7 = (1.4 - 0.7) - 0.0 + 0.0
Nov	0.1 = (0.0 - 0.0) + 0.1 + 0.0
Dec	0.8 = (0.0 - 0.0) + 0.8 + 0.0
Yr	13.4 = (23.4-10.9) + 0.9 + 0.0
1969	
Jan	1.3 = (0.0 - 0.0) + 1.3 + 0.0
Feb	0.2 = (0.0 - 0.0) + 0.2 + 0.0
Mar	0.4 = (0.0 - 0.0) + 0.4 + 0.0
Apr	0.4 = (2.1 - 0.7) - 1.0 + 0.0
May	1.0 = (3.4 - 1.5) - 0.9 + 0.0
Jun	0.8 = (4.2 - 2.9) - 0.6 + 0.0
Jul	2.0 = (5.2 - 3.0) - 0.2 + 0.0
Aug	0.2 = (5.1 - 4.9) - 0.1 + 0.0
Sept	0.8 = (3.1 - 2.4) + 0.0 + 0.0
Oct	1.1 = (0.4 - 0.0) + 0.7 + 0.0
Nov	0.1 = (0.3 - 0.1) + 0.0 + 0.0
Dec	0.3 = (0.0 - 0.0) + 0.3 + 0.0
Yr	8.6 = (23.9-15.4) + 0.1 + 0.0

TABLE 4.2b

ANNUAL WATER BALANCE

STATION: MEDICINE HAT

SOIL MOISTURE STORAGE CAPACITY = 4.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970

Jan 1.5 = (0.0 - 0.0) + 1.5 + 0.0
Feb 0.2 = (0.0 - 0.0) + 0.2 + 0.0
Mar 0.4 = (0.0 - 0.0) + 0.4 + 0.0
Apr 0.9 = (1.0 - 0.0) + 0.0 + 0.0
May 0.9 = (3.3 - 1.0) - 1.4 + 0.0
Jun 5.0 = (5.3 - 0.2) - 0.1 + 0.0
Jul 2.0 = (5.8 - 2.8) - 1.0 + 0.0
Aug 0.4 = (5.0 - 4.2) - 0.4 + 0.0
Sept 0.8 = (2.4 - 1.5) - 0.1 + 0.0
Oct 0.9 = (0.8 - 0.0) + 0.1 + 0.0
Nov 0.7 = (0.0 - 0.0) + 0.7 + 0.0
Dec 0.5 = (0.0 - 0.0) + 0.5 + 0.0

Yr 14.2 = (23.6- 9.7) + 0.4 + 0.0

1971

Jan 1.7 = (0.0 - 0.0) + 1.7 + 0.0
Feb 0.3 = (0.0 - 0.0) + 0.3 + 0.0
Mar 0.6 = (0.0 - 0.0) + 0.6 + 0.0
Apr 0.4 = (1.5 - 0.1) - 1.0 + 0.0
May 1.8 = (3.5 - 0.7) - 1.0 + 0.0
Jun 1.6 = (4.3 - 1.8) - 1.0 - 0.0
Jul 0.4 = (5.0 - 4.0) - 0.7 + 0.0
Aug 0.8 = (5.8 - 4.8) - 0.2 + 0.0
Sept 1.1 = (2.4 - 1.3) - 0.0 + 0.0
Oct 0.7 = (1.1 - 1.3) + 0.0 + 0.0
Nov 0.4 = (0.0 - 0.0) + 0.4 + 0.0
Dec 0.5 = (0.0 - 0.0) + 0.5 + 0.0

Yr 10.2 = (23.7-13.0) - 0.4 + 0.0

TABLE 4.3a

ANNUAL WATER BALANCE

STATION 1: BENCH MARK SITE

SOIL MOISTURE STORAGE CAPACITY = 6.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1968	
Jan	6.0 = (0.0 - 0.0) + 6.0 + 0.0
Feb	0.5 = (0.0 - 0.0) + 0.0 + 0.5
Mar	0.2 = (0.4 - 0.0) - 0.2 + 0.0
Apr	1.3 = (0.0 - 0.0) + 0.2 + 1.1
May	1.5 = (1.9 - 0.0) - 0.4 + 0.0
Jun	5.3 = (3.8 - 0.0) + 0.4 + 1.1
Jul	2.2 = (4.8 - 0.5) - 2.1 + 0.0
Aug	1.0 = (3.9 - 1.4) - 1.5 + 0.0
Sept	1.7 = (2.5 - 0.5) - 0.3 + 0.0
Oct	1.6 = (0.9 - 0.0) + 0.7 + 0.0
Nov	0.2 = (0.0 - 0.0) + 0.2 + 0.0
Dec	1.8 = (0.0 - 0.0) + 1.8 + 0.0
Yr	23.3 = (18.2- 2.4) + 4.8 + 2.7
1969	
Jan	3.2 = (0.0 - 0.0) + 1.2 + 2.0
Feb	0.6 = (0.0 - 0.0) + 0.0 + 0.6
Mar	0.9 = (0.0 - 0.0) + 0.0 + 0.9
Apr	1.0 = (1.8 - 0.1) - 0.8 + 0.0
May	4.3 = (2.8 - 0.0) + 0.8 + 0.8
Jun	2.9 = (3.4 - 0.0) - 0.5 + 0.0
Jul	2.0 = (4.5 - 0.6) - 1.8 + 0.0
Aug	0.5 = (4.8 - 2.4) - 1.9 + 0.0
Sept	1.6 = (2.6 - 0.7) - 0.3 + 0.0
Oct	3.0 = (0.5 - 0.0) + 2.6 + 0.0
Nov	0.3 = (0.3 - 0.0) + 0.0 + 0.0
Dec	0.8 = (0.0 - 0.0) + 0.8 + 0.0
Yr	21.1 = (20.6- 3.8) + 0.0 + 4.3

TABLE 4.3b

ANNUAL WATER BALANCE

STATION 1: BENCH MARK SITE

SOIL MOISTURE STORAGE CAPACITY = 6.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970	
Jan	4.1 = (0.0 - 0.0) + 1.1 + 2.9
Feb	0.5 = (0.0 - 0.0) + 0.0 + 0.5
Mar	1.2 = (0.0 - 0.0) + 0.0 + 1.2
Apr	2.6 = (0.0 - 0.0) + 0.0 + 2.6
May	1.1 = (2.6 - 0.2) - 1.3 + 0.0
Jun	7.4 = (4.5 - 0.0) + 1.3 + 1.6
Jul	1.7 = (4.9 - 0.7) - 2.5 + 0.0
Aug	0.1 = (4.4 - 2.6) - 1.8 + 0.0
Sept	1.4 = (2.2 - 0.5) - 0.2 + 0.0
Oct	2.3 = (0.9 - 0.0) + 1.4 + 0.0
Nov	1.8 = (0.0 - 0.0) + 1.8 + 0.0
Dec	1.2 = (0.0 - 0.0) + 1.2 + 0.0
Yr	25.5 = (19.6- 4.0) + 1.0 + 8.9
1971	
Jan	4.4 = (0.0 - 0.0) + 0.1 + 4.2
Feb	0.8 = (0.0 - 0.0) + 0.0 + 0.8
Mar	1.7 = (0.0 - 0.0) + 0.0 + 1.7
Apr	1.0 = (0.0 - 0.0) + 0.0 + 1.0
May	1.9 = (2.5 - 0.0) - 0.6 + 0.0
Jun	4.1 = (3.3 - 0.0) + 0.6 + 0.2
Jul	0.8 = (4.4 - 0.9) - 2.7 + 0.0
Aug	1.0 = (5.5 - 2.8) - 1.7 + 0.0
Sept	1.7 = (2.1 - 0.3) - 0.1 + 0.0
Oct	2.0 = (0.8 - 0.0) + 1.1 + 0.0
Nov	1.0 = (0.0 - 0.0) + 1.0 + 0.0
Dec	1.4 = (0.0 - 0.0) + 1.4 + 0.0
Yr	21.6 = (18.8- 4.0) - 0.9 + 7.8

TABLE 4.4a

ANNUAL WATER BALANCE

STATION 2: SUMMIT FOREST SITE

SOIL MOISTURE STORAGE CAPACITY = 6.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1968	
Jan	7.0 = (0.0 - 0.0) + 6.0 + 1.0
Feb	0.0 = (0.0 - 0.0) + 0.0 + 0.0
Mar	0.7 = (0.0 - 0.0) + 0.0 + 0.7
Apr	1.3 = (0.3 - 0.0) + 0.0 + 1.0
May	0.4 = (2.4 - 0.3) - 1.7 + 0.0
Jun	5.2 = (3.8 - 0.0) + 1.4 + 0.0
Jul	1.6 = (4.8 - 0.8) - 2.4 + 0.0
Aug	1.0 = (3.8 - 1.5) - 1.3 + 0.0
Sept	0.4 = (2.4 - 1.4) - 0.6 + 0.0
Oct	1.9 = (0.7 - 0.0) + 1.2 + 0.0
Nov	0.3 = (0.0 - 0.0) + 0.3 + 0.0
Dec	2.1 = (0.0 - 0.0) + 2.1 + 0.0
Yr	22.0 = (18.1- 4.0) + 5.1 + 2.7
1969	
Jan	3.7 = (0.0 - 0.0) + 0.9 + 2.9
Feb	0.7 = (0.0 - 0.0) + 0.0 + 0.7
Mar	1.1 = (0.0 - 0.0) + 0.0 + 1.1
Apr	1.1 = (1.5 - 0.0) - 0.4 + 0.0
May	3.9 = (2.7 - 0.0) + 0.4 + 0.8
Jun	3.2 = (3.5 - 0.0) - 0.3 + 0.0
Jul	1.6 = (4.5 - 0.7) - 2.2 + 0.0
Aug	0.4 = (4.8 - 2.6) - 1.8 + 0.0
Sept	0.7 = (2.7 - 1.5) - 0.5 + 0.0
Oct	3.5 = (0.0 - 0.0) + 3.5 + 0.0
Nov	0.3 = (0.0 - 0.0) + 0.3 + 0.0
Dec	0.9 = (0.0 - 0.0) + 0.9 + 0.0
Yr	21.2 = (19.8- 4.9) + 0.8 + 5.5

TABLE 4.4b

ANNUAL WATER BALANCE

STATION 2: SUMMIT FOREST SITE

SOIL MOISTURE STORAGE CAPACITY = 6.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970

Jan 4.8 = (0.0 - 0.0) + 0.0 + 4.8
Feb 0.6 = (0.0 - 0.0) + 0.0 + 0.6
Mar 1.4 = (0.0 - 0.0) + 0.0 + 1.4
Apr 3.0 = (0.0 - 0.0) + 0.0 + 3.0
May 0.9 = (2.5 - 0.2) - 1.5 + 0.0
Jun 7.5 = (4.5 - 0.0) + 1.5 + 1.6
Jul 1.6 = (4.9 - 0.8) - 2.6 + 0.0
Aug 0.4 = (4.5 - 2.4) - 1.7 + 0.0
Sept 1.2 = (2.3 - 0.8) - 0.3 + 0.0
Oct 2.7 = (0.6 - 0.0) + 2.2 + 0.0
Nov 2.1 = (0.0 - 0.0) + 2.1 + 0.0
Dec 1.4 = (0.0 - 0.0) + 0.3 + 1.1

Yr 27.7 = (19.3- 4.2) + 0.0 +12.5

1971

Jan 5.1 = (0.0 - 0.0) - 1.1 + 6.2
Feb 0.9 = (0.0 - 0.0) + 0.0 + 0.9
Mar 1.9 = (0.0 - 0.0) + 0.0 + 1.9
Apr 1.1 = (0.6 - 0.0) + 0.0 + 0.5
May 2.0 = (2.8 - 0.0) - 0.7 + 0.0
Jun 3.1 = (3.0 - 0.0) + 0.1 + 0.0
Jul 0.6 = (4.4 - 1.3) - 2.5 + 0.0
Aug 0.7 = (5.2 - 3.0) - 1.5 + 0.0
Sept 1.9 = (2.5 - 0.5) - 0.1 + 0.0
Oct 2.3 = (0.7 - 0.0) + 1.6 + 0.0
Nov 1.2 = (0.0 - 0.0) + 1.2 + 0.0
Dec 1.6 = (0.0 - 0.0) + 1.6 + 0.0

Yr 22.6 = (19.4- 4.8) - 1.5 + 9.5

TABLE 4.5a

ANNUAL WATER BALANCE

STATION 3: WEST SUMMIT PLATEAU

SOIL MOISTURE STORAGE CAPACITY = 6.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1968

Jan 6.0 = (0.0 - 0.0) + 6.0 + 0.0
Feb 0.0 = (0.0 - 0.0) + 0.0 + 0.0
Mar 0.1 = (0.3 - 0.0) - 0.2 + 0.0
Apr 1.0 = (0.5 - 0.0) + 0.2 + 0.3
May 1.3 = (2.3 - 0.1) - 0.9 + 0.0
Jun 4.5 = (3.7 - 0.0) + 0.8 + 0.0
Jul 1.6 = (4.7 - 0.7) - 2.4 + 0.0
Aug 1.2 = (3.9 - 1.4) - 1.3 + 0.0
Sept 0.3 = (2.7 - 1.7) - 0.7 + 0.0
Oct 0.4 = (1.1 - 0.6) - 0.2 + 0.0
Nov 0.4 = (0.0 - 0.0) + 0.4 + 0.0
Dec 1.9 = (0.0 - 0.0) + 1.9 + 0.0

Yr 18.8 = (19.3 -4.4) + 3.6 + 0.3

1969

Jan 3.5 = (0.0 - 0.0) + 2.4 + 1.1
Feb 1.2 = (0.0 - 0.0) + 0.0 + 1.2
Mar 0.3 = (0.0 - 0.0) + 0.0 + 0.3
Apr 1.0 = (1.8 - 0.0) - 0.7 + 0.0
May 0.3 = (2.8 - 0.7) - 1.8 + 0.0
Jun 3.0 = (3.4 - 0.2) - 0.2 + 0.0
Jul 1.3 = (4.5 - 1.9) - 1.4 + 0.0
Aug 0.5 = (4.9 - 3.5) - 1.0 + 0.0
Sept 0.5 = (2.9 - 2.1) - 0.3 + 0.0
Oct 2.2 = (0.2 - 0.0) + 1.9 + 0.0
Nov 0.1 = (0.3 - 0.2) - 0.1 + 0.0
Dec 0.4 = (0.0 - 0.0) + 0.4 + 0.0

Yr 14.2 = (20.8- 8/5) - 0.8 + 2.7

TABLE 4.5b

ANNUAL WATER BALANCE

STATION 3: WEST SUMMIT PLATEAU

SOIL MOISTURE STORAGE CAPACITY = 6.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970

Jan 1.6 = (0.0 - 0.0) + 1.6 + 0.0
Feb 0.9 = (0.0 - 0.0) + 0.9 + 0.0
Mar 1.3 = (0.0 - 0.0) + 0.6 + 0.7
Apr 1.5 = (0.0 - 0.0) + 0.0 + 1.5
May 1.0 = (2.5 - 0.2) - 1.4 + 0.0
Jun 7.6 = (4.5 - 0.0) + 1.4 + 1.8
Jul 1.1 = (4.9 - 1.0) - 2.8 + 0.0
Aug 0.6 = (4.6 - 2.4) - 1.5 + 0.0
Sept 1.2 = (2.3 - 0.9) - 0.3 + 0.0
Oct 0.5 = (1.0 - 0.4) - 0.1 + 0.0
Nov 1.2 = (0.0 - 0.0) + 1.2 + 0.0
Dec 2.6 = (0.0 - 0.0) + 2.6 + 0.0

Yr 21.3 = (19.8- 4.8) + 2.3 + 4.0

1971

Jan 4.8 = (0.0 - 0.0) + 0.9 + 3.9
Feb 0.7 = (0.0 - 0.0) + 0.0 + 0.7
Mar 0.9 = (0.0 - 0.0) + 0.0 + 0.9
Apr 1.6 = (0.2 - 0.0) + 0.0 + 1.4
May 1.4 = (2.7 - 0.1) - 1.1 + 0.0
Jun 4.1 = (3.1 - 0.0) + 1.0 + 0.0
Jul 0.9 = (4.6 - 1.0) - 2.7 + 0.0
Aug 0.8 = (5.6 - 3.1) - 1.7 + 0.0
Sept 1.4 = (1.9 - 0.4) - 0.1 + 0.0
Oct 1.0 = (0.9 - 0.0) + 0.1 + 0.0
Nov 0.4 = (0.0 - 0.0) + 0.4 + 0.0
Dec 1.6 = (0.0 - 0.0) + 1.6 + 0.0

Yr 19.7 = (19.1- 4.6) - 1.7 + 6.9

TABLE 4.6a

ANNUAL WATER BALANCE

STATION 4: WEST PLATEAU SLOPE

SOIL MOISTURE STORAGE CAPACITY = 5.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1968	
Jan	6.0 = (0.0 - 0.0) + 5.0 + 1.0
Feb	0.1 = (0.0 - 0.0) + 0.0 + 0.1
Mar	0.0 = (0.2 - 0.0) - 0.2 + 0.0
Apr	0.7 = (0.9 - 0.0) - 0.2 + 0.0
May	1.3 = (2.5 - 0.2) - 1.0 + 0.0
Jun	4.0 = (3.9 - 0.0) - 0.1 + 0.0
Jul	1.0 = (4.7 - 1.7) - 1.9 + 0.0
Aug	1.2 = (3.9 - 2.0) - 0.8 + 0.0
Sept	0.2 = (2.8 - 2.2) - 0.4 + 0.0
Oct	0.4 = (1.2 - 0.7) - 0.1 + 0.0
Nov	0.4 = (0.0 - 0.0) + 0.4 + 0.0
Dec	2.1 = (0.0 - 0.0) + 2.1 + 0.0
Yr	17.4 = (20.0- 6.8) + 3.0 + 1.1
1969	
Jan	3.8 = (0.0 - 0.0) + 2.0 + 1.9
Feb	1.3 = (0.0 - 0.0) + 0.0 + 1.3
Mar	0.4 = (0.0 - 0.0) + 0.0 + 0.4
Apr	1.1 = (1.9 - 0.1) - 0.8 + 0.0
May	3.0 = (3.0 - 0.0) + 0.0 + 0.0
Jun	2.1 = (3.5 - 0.3) - 1.0 + 0.0
Jul	0.9 = (4.6 - 2.0) - 1.7 + 0.0
Aug	0.4 = (4.9 - 3.6) - 0.9 + 0.0
Sept	0.5 = (2.8 - 2.0) - 0.2 + 0.0
Oct	2.4 = (0.0 - 0.0) + 2.4 + 0.0
Nov	0.1 = (0.0 - 0.0) + 0.1 + 0.0
Dec	0.4 = (0.0 - 0.0) + 0.4 + 0.0
Yr	16.4 = (20.7- 8.1) + 0.2 + 3.6

TABLE 4.6b

ANNUAL WATER BALANCE

STATION 4: WEST PLATEAU SLOPE

SOIL MOISTURE STORAGE CAPACITY = 5.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970

Jan	1.8 = (0.0 - 0.0) + 1.7 + 0.1
Feb	1.0 = (0.0 - 0.0) + 0.0 + 1.0
Mar	1.4 = (0.0 - 0.0) + 0.0 + 1.4
Apr	1.6 = (0.0 - 0.0) + 0.0 + 1.6
May	0.8 = (2.8 - 0.3) - 1.6 + 0.0
Jun	5.8 = (4.7 - 0.0) + 1.1 + 0.0
Jul	1.1 = (5.1 - 1.5) - 2.4 + 0.0
Aug	0.7 = (4.6 - 2.8) - 1.1 + 0.0
Sept	1.1 = (2.2 - 0.9) - 0.2 + 0.0
Oct	0.5 = (0.7 - 0.1) - 0.0 + 0.0
Nov	1.3 = (0.0 - 0.0) + 1.3 + 0.0
Dec	2.8 = (0.0 - 0.0) + 2.8 + 0.0
Yr	20.1 = (20.0- 5.6) + 1.6 + 4.1

1971

Jan	5.2 = (0.0 - 0.0) + 0.1 + 5.2
Feb	0.7 = (0.0 - 0.0) + 0.0 + 0.7
Mar	1.0 = (0.0 - 0.0) + 0.0 + 1.0
Apr	1.8 = (1.0 - 0.0) + 0.0 + 0.8
May	1.2 = (3.1 - 0.3) - 1.5 + 0.0
Jun	3.8 = (3.5 - 0.0) + 0.3 + 0.0
Jul	1.0 = (4.3 - 1.4) - 1.8 + 0.0
Aug	7.3 = (5.1 - 0.0) + 2.2 + 0.0
Sept	1.5 = (1.9 - 0.1) - 0.4 + 0.0
Oct	1.1 = (1.2 - 0.0) + 0.0 + 0.0
Nov	0.4 = (0.0 - 0.0) + 0.4 + 0.0
Dec	1.8 = (0.0 - 0.0) + 0.8 + 0.9
Yr	26.9 = (20.1- 1.8) + 0.1 + 8.6

TABLE 4.7a

ANNUAL WATER BALANCE

STATION 5: NORTH SLOPE FOREST

SOIL MOISTURE STORAGE CAPACITY = 5.0 INCHES

Ppt = (PE - D) ± ΔSt + Sur

1968	
Jan	6.0 = (0.0 - 0.0) + 5.0 + 1.0
Feb	0.0 = (0.0 - 0.0) + 0.0 + 0.0
Mar	0.0 = (0.5 - 0.0) - 0.4 + 0.0
Apr	0.5 = (0.9 - 0.0) - 0.4 + 0.0
May	1.2 = (2.6 - 0.4) - 1.0 + 0.0
Jun	4.2 = (3.8 - 0.0) + 0.5 + 0.0
Jul	1.3 = (4.7 - 1.6) - 1.8 + 0.0
Aug	1.0 = (3.9 - 2.1) - 0.8 + 0.0
Sept	0.3 = (2.9 - 2.2) - 0.4 + 0.0
Oct	1.4 = (1.2 - 0.0) + 0.1 + 0.0
Nov	0.2 = (0.0 - 0.0) + 0.2 + 0.0
Dec	1.5 = (0.0 - 0.0) + 1.5 + 0.0
Yr	17.7 = (20.5- 6.3) + 2.5 + 1.0
1969	
Jan	2.7 = (0.0 - 0.0) + 2.5 + 0.1
Feb	0.5 = (0.0 - 0.0) + 0.0 + 0.5
Mar	0.8 = (0.0 - 0.0) + 0.0 + 0.8
Apr	0.8 = (2.1 - 0.1) - 1.2 + 0.0
May	0.6 = (2.9 - 0.9) - 1.4 + 0.0
Jun	2.2 = (3.4 - 0.7) - 0.5 + 0.0
Jul	1.2 = (4.6 - 2.5) - 0.9 + 0.0
Aug	0.5 = (5.0 - 3.9) - 0.6 + 0.0
Sept	0.4 = (2.9 - 2.4) - 0.2 + 0.0
Oct	2.5 = (0.0 - 0.0) + 2.5 + 0.0
Nov	0.3 = (0.0 - 0.0) + 0.2 + 0.0
Dec	0.6 = (0.0 - 0.0) + 0.6 + 0.0
Yr	13.2 = (21.1-10.4) + 1.1 + 1.4

TABLE 4.7b

ANNUAL WATER BALANCE

STATION 5: NORTH SLOPE FOREST

SOIL MOISTURE STORAGE CAPACITY = 5.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970	
Jan	3.4 = (0.0 - 0.0) + 1.4 + 2.1
Feb	0.4 = (0.0 - 0.0) + 0.0 + 0.4
Mar	1.0 = (0.0 - 0.0) + 0.0 + 1.0
Apr	2.2 = (0.1 - 0.0) + 0.0 + 2.1
May	0.9 = (2.6 - 0.3) - 1.5 + 0.0
Jun	6.9 = (4.7 - 0.0) + 1.5 + 0.7
Jul	1.1 = (5.0 - 1.2) - 2.8 + 0.0
Aug	0.6 = (4.6 - 2.8) - 1.2 + 0.0
Sept	1.3 = (2.3 - 0.9) - 0.2 + 0.0
Oct	2.0 = (0.9 - 0.0) + 1.0 + 0.0
Nov	1.5 = (0.0 - 0.0) + 1.5 + 0.0
Dec	1.0 = (0.0 - 0.0) + 1.0 + 0.0
Yr	22.3 = (20.3- 5.1) + 0.7 + 6.3
1971	
Jan	3.7 = (0.0 - 0.0) + 0.6 + 3.0
Feb	0.6 = (0.0 - 0.0) + 0.0 + 0.6
Mar	1.4 = (0.0 - 0.0) + 0.0 + 1.4
Apr	0.8 = (0.4 - 0.0) + 0.0 + 0.4
May	1.2 = (3.0 - 0.3) - 1.5 + 0.0
Jun	3.7 = (3.4 - 0.0) + 0.3 + 0.0
Jul	0.9 = (4.5 - 1.6) - 2.0 + 0.0
Aug	0.6 = (5.4 - 3.6) - 1.1 + 0.0
Sept	1.3 = (2.0 - 0.7) - 0.1 + 0.0
Oct	1.7 = (1.3 - 0.0) + 0.4 + 0.0
Nov	0.8 = (0.0 - 0.0) + 0.8 + 0.0
Dec	1.2 = (0.0 - 0.0) + 1.2 + 0.0
Yr	18.0 = (20.0- 6.1) - 1.4 + 5.5

TABLE 4.8a

ANNUAL WATER BALANCE

STATION 6: OPEN VALLEY

SOIL MOISTURE STORAGE CAPACITY = 4.0 INCHES

$$\text{Ppt} = (\text{PE} - \text{D}) \pm \Delta\text{St} + \text{Sur}$$

1968

Jan	1.1 = (0.0 - 0.0) + 1.1 + 0.0
Feb	0.6 = (0.0 - 0.0) + 0.6 + 0.0
Mar	0.0 = (0.6 - 0.3) - 0.2 + 0.0
Apr	1.1 = (0.8 - 0.0) + 0.3 + 0.0
May	1.0 = (2.5 - 0.9) - 0.6 + 0.0
Jun	4.4 = (3.9 - 0.0) + 0.5 + 0.0
Jul	1.0 = (4.8 - 2.6) - 1.1 + 0.0
Aug	1.0 = (4.0 - 2.6) - 0.4 + 0.0
Sept	0.2 = (2.6 - 2.3) - 0.1 + 0.0
Oct	0.6 = (1.1 - 0.5) - 0.0 + 0.0
Nov	0.1 = (0.0 - 0.0) + 0.1 + 0.0
Dec	0.6 = (0.0 - 0.0) + 0.6 + 0.0
Yr	11.9 = (20.2- 9.2) + 0.9 + 0.0

1969

Jan	1.1 = (0.0 - 0.0) + 1.1 + 0.0
Feb	0.2 = (0.0 - 0.0) + 0.2 + 0.0
Mar	0.3 = (0.0 - 0.0) + 0.3 + 0.0
Apr	0.3 = (1.9 - 0.8) - 0.8 + 0.0
May	0.6 = (2.9 - 1.6) - 0.7 + 0.0
Jun	1.8 = (3.6 - 1.4) - 0.3 + 0.0
Jul	0.9 = (4.7 - 3.4) - 0.4 + 0.0
Aug	0.6 = (4.8 - 4.1) - 0.1 + 0.0
Sept	0.4 = (2.7 - 2.2) + 0.0 + 0.0
Oct	1.0 = (0.4 - 0.0) + 0.6 + 0.0
Nov	0.1 = (0.0 - 0.0) + 0.1 + 0.0
Dec	0.3 = (0.0 - 0.0) + 0.3 + 0.0
Yr	7.8 = (21.0-13.4) + 0.2 + 0.0

TABLE 4.8b

ANNUAL WATER BALANCE

STATION 6: OPEN VALLEY

SOIL MOISTURE STORAGE CAPACITY = 4.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970

Jan 1.4 = (0.0 - 0.0) + 1.4 + 0.0
Feb 0.2 = (0.0 - 0.0) + 0.2 + 0.0
Mar 0.4 = (0.0 - 0.0) + 0.4 + 0.0
Apr 0.9 = (0.5 - 0.0) + 0.4 + 0.0
May 0.6 = (3.1 - 0.8) - 1.6 + 0.0
Jun 6.5 = (4.7 - 0.0) + 1.7 + 0.0
Jul 1.2 = (5.2 - 1.6) - 2.3 + 0.0
Aug 0.6 = (4.5 - 3.1) - 0.8 + 0.0
Sept 1.1 = (2.3 - 1.0) - 0.1 + 0.0
Oct 0.8 = (0.6 - 0.0) + 0.2 + 0.0
Nov 0.6 = (0.0 - 0.0) + 0.6 + 0.0
Dec 0.4 = (0.0 - 0.0) + 0.4 + 0.0

Yr 14.9 = (20.9- 6.5) + 0.5 + 0.0

1971

Jan 1.5 = (0.0 - 0.0) + 1.5 + 0.0
Feb 0.3 = (0.0 - 0.0) + 0.3 + 0.0
Mar 0.6 = (0.0 - 0.0) + 0.6 + 0.0
Apr 0.3 = (1.3 - 0.1) - 0.9 + 0.0
May 1.3 = (3.3 - 0.8) - 1.2 + 0.0
Jun 3.2 = (3.8 - 0.4) - 0.3 + 0.0
Jul 0.6 = (4.4 - 2.8) - 1.0 + 0.0
Aug 0.5 = (5.2 - 4.2) - 0.4 + 0.0
Sept 1.2 = (1.6 - 0.4) + 0.0 + 0.0
Oct 0.7 = (1.0 - 0.3) + 0.0 + 0.0
Nov 0.3 = (0.0 - 0.0) + 0.3 + 0.0
Dec 0.5 = (0.0 - 0.0) + 0.5 + 0.0

Yr 11.1 = (20.7- 9.0) - 0.6 + 0.0

TABLE 4.9a

ANNUAL WATER BALANCE

STATION 7: NORTH PRAIRIE

SOIL MOISTURE STORAGE CAPACITY = 4.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1968

Jan $0.2 = (0.0 - 0.0) + 0.2 + 0.0$
Feb $0.0 = (0.0 - 0.0) + 0.0 + 0.0$
Mar $0.0 = (1.0 - 0.9) + 0.0 + 0.0$
Apr $0.1 = (1.0 - 0.8) + 0.0 + 0.0$
May $2.0 = (2.7 - 0.7) + 0.0 + 0.0$
Jun $3.1 = (3.9 - 0.7) + 0.0 + 0.0$
Jul $1.6 = (5.0 - 3.3) - 0.1 + 0.0$
Aug $0.7 = (4.1 - 3.4) + 0.0 + 0.0$
Sept $0.2 = (2.9 - 2.7) + 0.0 + 0.0$
Oct $0.1 = (1.3 - 1.2) + 0.0 + 0.0$
Nov $0.1 = (0.0 - 0.0) + 0.1 + 0.0$
Dec $0.7 = (0.0 - 0.0) + 0.7 + 0.0$

Yr $9.0 = (21.9-13.7) + 0.8 + 0.0$

1969

Jan $1.2 = (0.0 - 0.0) + 1.2 + 0.0$
Feb $0.4 = (0.0 - 0.0) + 0.4 + 0.0$
Mar $0.1 = (0.0 - 0.0) + 0.1 + 0.0$
Apr $0.3 = (2.3 - 1.0) - 1.0 + 0.0$
May $0.4 = (3.2 - 2.0) - 0.8 + 0.0$
Jun $2.1 = (3.7 - 1.4) - 0.3 + 0.0$
Jul $1.2 = (4.8 - 3.3) - 0.3 + 0.0$
Aug $0.3 = (5.2 - 4.7) - 0.1 + 0.0$
Sept $0.4 = (2.9 - 2.4) + 0.0 + 0.0$
Oct $0.8 = (0.7 - 0.0) + 0.0 + 0.0$
Nov $0.0 = (0.3 - 0.3) + 0.0 + 0.0$
Dec $0.1 = (0.0 - 0.0) + 0.1 + 0.0$

Yr $7.4 = (23.2-15.1) - 0.6 + 0.0$

TABLE 4.9b

ANNUAL WATER BALANCE

STATION 7: NORTH PRAIRIE

SOIL MOISTURE STORAGE CAPACITY 4.0 = INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970	
Jan	0.6 = (0.0 - 0.0) + 0.6 + 0.0
Feb	0.3 = (0.0 - 0.0) + 0.3 + 0.0
Mar	0.4 = (0.0 - 0.0) + 0.4 + 0.0
Apr	0.5 = (0.6 - 0.0) + 0.0 + 0.0
May	0.3 = (2.8 - 1.8) - 0.7 + 0.0
Jun	6.9 = (4.9 - 0.0) + 2.0 + 0.0
Jul	0.4 = (5.5 - 3.0) - 2.0 + 0.0
Aug	0.6 = (5.0 - 3.8) - 0.5 + 0.0
Sept	1.6 = (2.1 - 0.5) + 0.0 + 0.0
Oct	0.2 = (0.6 - 0.4) + 0.0 + 0.0
Nov	0.4 = (0.0 - 0.0) + 0.4 + 0.0
Dec	0.9 = (0.0 - 0.0) + 0.9 + 0.0
Yr	13.2 = (21.5- 9.6) + 1.4 + 0.0
1971	
Jan	1.7 = (0.0 - 0.0) + 1.7 + 0.0
Feb	0.2 = (0.0 - 0.0) + 0.2 + 0.0
Mar	0.3 = (0.0 - 0.0) + 0.3 + 0.0
Apr	0.6 = (0.5 - 0.0) + 0.1 + 0.0
May	1.6 = (2.8 - 0.2) - 1.1 + 0.0
Jun	2.7 = (3.4 - 0.3) - 0.5 + 0.0
Jul	1.6 = (5.0 - 2.0) - 1.4 + 0.0
Aug	1.2 = (5.5 - 3.7) - 0.7 + 0.0
Sept	1.2 = (2.7 - 1.3) - 0.1 + 0.0
Oct	0.4 = (1.3 - 0.9) + 0.0 + 0.0
Nov	0.1 = (0.0 - 0.0) + 0.1 + 0.0
Dec	0.6 = (0.0 - 0.0) + 0.6 + 0.0
Yr	12.1 = (21.2- 8.4) - 0.7 + 0.0

TABLE 4.10a

ANNUAL WATER BALANCE

STATION 8: SOUTH PRAIRIE

SOIL MOISTURE STORAGE CAPACITY = 4.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1968

Jan 0.2 = (0.0 - 0.0) + 0.2 + 0.0
Feb 0.3 = (0.0 - 0.0) + 0.3 + 0.0
Mar 0.0 = (0.4 - 0.4) - 0.1 + 0.0
Apr 0.4 = (1.1 - 0.6) - 0.1 + 0.0
May 0.4 = (2.3 - 1.7) - 0.1 + 0.0
Jun 2.2 = (4.0 - 1.7) - 0.1 + 0.0
Jul 0.6 = (5.1 - 4.4) - 0.1 + 0.0
Aug 1.4 = (4.2 - 2.7) + 0.0 + 0.0
Sept 0.2 = (2.7 - 2.5) + 0.0 + 0.0
Oct 0.2 = (1.2 - 1.0) + 0.0 + 0.0
Nov 0.2 = (0.0 - 0.0) + 0.2 + 0.0
Dec 0.8 = (0.0 - 0.0) + 0.8 + 0.0

Yr 6.9 = (21.0-15.0) + 1.0 + 0.0

1969

Jan 1.5 = (0.0 - 0.0) + 1.5 + 0.0
Feb 0.5 = (0.0 - 0.0) + 0.5 + 0.0
Mar 0.1 = (0.0 - 0.0) + 0.1 + 0.0
Apr 0.4 = (1.7 - 0.4) - 0.9 + 0.0
May 2.1 = (3.3 - 0.6) - 0.6 + 0.0
Jun 2.2 = (3.7 - 1.0) - 0.5 + 0.0
Jul 1.5 = (4.8 - 2.7) - 0.6 + 0.0
Aug 0.2 = (5.1 - 4.6) - 0.4 + 0.0
Sept 0.6 = (3.0 - 2.3) - 0.1 + 0.0
Oct 0.9 = (0.0 - 0.0) + 0.9 + 0.0
Nov 0.0 = (0.0 - 0.0) + 0.0 + 0.0
Dec 0.2 = (0.0 - 0.0) + 0.2 + 0.0

Yr 10.2 = (21.6-11.6) + 0.2 + 0.0

TABLE 4.10b

ANNUAL WATER BALANCE

STATION 8: SOUTH PRAIRIE

SOIL MOISTURE STORAGE CAPACITY = 4.0 INCHES

$$Ppt = (PE - D) \pm \Delta St + Sur$$

1970

Jan 0.7 = (0.0 - 0.0) + 0.7 + 0.0
Feb 0.4 = (0.0 - 0.0) + 0.4 + 0.0
Mar 0.5 = (0.0 - 0.0) + 0.5 + 0.0
Apr 0.6 = (0.2 - 0.0) + 0.4 + 0.0
May 2.1 = (2.8 - 0.2) - 0.5 + 0.0
Jun 1.2 = (4.8 - 2.0) - 1.6 + 0.0
Jul 0.7 = (5.3 - 3.8) - 0.7 + 0.0
Aug 0.2 = (4.8 - 4.4) - 0.2 + 0.0
Sept 0.0 = (2.4 - 2.3) + 0.0 + 0.0
Oct 0.2 = (0.7 - 0.5) + 0.0 + 0.0
Nov 0.5 = (0.0 - 0.0) + 0.5 + 0.0
Dec 1.1 = (0.0 - 0.0) + 1.1 + 0.0

Yr 8.3 = (21.0-13.2) + 0.5 + 0.0

1971

Jan 2.0 = (0.0 - 0.0) + 2.0 + 0.0
Feb 0.3 = (0.0 - 0.0) + 0.3 + 0.0
Mar 0.4 = (0.0 - 0.0) + 0.0 + 0.4
Apr 0.7 = (0.5 - 0.0) + 0.0 + 0.2
May 0.5 = (2.7 - 0.5) - 1.7 + 0.0
Jun 2.2 = (3.8 - 0.8) - 0.7 + 0.0
Jul 1.0 = (4.7 - 2.8) - 0.9 + 0.0
Aug 0.3 = (5.6 - 4.9) - 0.4 + 0.0
Sept 0.7 = (2.2 - 1.4) + 0.0 + 0.0
Oct 0.4 = (1.2 - 0.7) + 0.0 + 0.0
Nov 0.1 = (0.0 - 0.0) + 0.1 + 0.0
Dec 0.7 = (0.0 - 0.0) + 0.7 + 0.0

Yr 9.4 = (20.7-11.2) - 0.8 + 0.6

for runoff is assumed to be equal to the monthly runoff. This is justified because of the flashy nature of prairie streamflow.

It must be mentioned that one of the major concerns here in the computation of water balance is to provide an estimate of the total annual runoff. No attempt is made to produce the annual discharge hydrograph using the Thornthwaite technique. In the Thornthwaite Water Balance computation procedure, it is assumed that the beginning of snowmelt runoff occurs in the first month when mean monthly temperature rises above 31.2^{O}F (-1^{O}C). 31.2^{O}F (-1^{O}C) is chosen as the threshold monthly mean temperature under the assumption that, with mean monthly temperature below 31.2^{O}F, precipitation falls as snow, which remains on ground. (Thornthwaite, 1957, p. 191). Snowmelt runoff is the major source of streamflow in the study area; the total reliance of the hydrograph on a threshold temperature value would greatly oversimplify the situation. There is abundant evidence that runoff occurs in months with sub-freezing monthly mean temperature. This may be due to chinook effects. In spring months in the study area, when the mean monthly temperature may only differ little from the threshold temperature (31.2^{O}F), warm spells of weather may be frequent and high runoff is extremely likely in months with mean temperature below 31.2^{O}F. It is considered more appropriate to use statistical techniques to estimate the occurrence time of discharge peak.

4.3 The Distribution of Water Surplus

The temporal and spatial distribution of water surplus can be observed from the results of the water balance computation. The water yield from the low level stations was found to be very little, and this little surplus, if present, occurred mainly in the late winter months. Negligible evapotranspiration (The Thornthwaite procedure assumes no net loss due to evapotranspiration under sub-freezing temperatures) during winter allowed the comparatively little precipitation to go into soil moisture recharge in the beginning winter months and become surplus in late winter. Temperature conditions would cause the accumulation of the surplus water until spring snowmelt before runoff occurred. The high level crest stations generally went through a more extended surplus-producing period, and very often surpluses occurred through spring and during early summer months. The slope stations also tended to follow the pattern of the crest stations and are runoff producing.

From the results of the water balance computation, the precipitation at some stations during summer and fall was evaporated directly or stored in soil and no runoff was produced. This is at variance with the observed runoff pattern of some basins where a distinguishable minor peak can be found due to summer maximum of rain. In other cases, the observed runoff has its summer peak in July, rather than June, as suggested by the water balance results. The reason for this may be twofold:

(1) The low station density could not minitor efficiently the occurrences of summer storms which were probably very localized. The spatial and temporal variation of precipitation intensity in such storms could be very large. These storms were likely to be convective in nature and they probably occur-red frequently over the low level plains area where station network density was particularly sparce as well as in the hill areas.

(2) The general distribution of water balance condition was in such a manner that net surplus or deficit was regionalized. Even when uniform precipitation occurred over the basin area runoff could only be produced in a restricted low evapotranspiration zone and in low storage areas. Thornthwaite's approach to the estimation of evapotranspiration depends solely on one meteorological control - mean monthly temperature, which, in the case of the present study, was predominantly affected by the elevation of the meteorological sites. This partly explains why most of the high level stations have comparatively high total annual water surplus from the water balance computation, while the slope stations have less, and the plains stations are found to have produced little runoff.

Due to the considerable interpolation involved in the estimation of winter precipitation at the meteorological stations, (See Appendix), it is doubtful whether the individual numerical

values of the water balance components have any significant meaning beyond that of being logical approximations. However, it is expected that the results of the water balance computation should reveal the general spatial pattern of water surplus in spite of the interpolation involved. The trends and orientations of surplus isopleths are believed to be more elastic in responding to estimation errors. In other words, the isoline pattern shown have greater significance than the individual numerical values. In order to illustrate the surplus pattern, a series of water surplus maps was produced. Maximum use had been made of all available information in the production of the maps. Although there are apparent insufficiencies resulting from sparce station density, particularly at the lower levels, it is believed that the pattern of isolines in the area of the Cypress Hills plateau provides a good approximation to the actual situation of water yield. This is the result of greater station density in the area as well as the fairly homogeneous topography of the plateau crest.

4.4 The Production of the Surplus Maps

The drawing of surplus isopleths was based on several considerations:

(1) The computed water surplus at the meteorological stations.

(2) The topography of the study area as indicated by contour lines on the 1:250,000 N.T.S. maps.

(3) The climatological characteristics of the study area, especially in terms of storm tracks.

(4) The measured runoff at the discharge gauges. (hydrometric stations).

The surplus isopleth interval was determined individually for each year, dependent upon the moisture balance conditions. For a wet year, a greater interval was used in order to avoid confusion through use of an excessive number of isopleths. It was assumed that the area within the watershed bounded by two successive isopleths formed a zone of uniform water surplus, and this area was measured by a planimeter. It was also assumed that a quantity of runoff represented by the mean value of the two isopleths occurred uniformly over the area concerned. The lowest isopleth was taken as the 0.5 inch line, below which runoff was assumed to be negligible. Since runoff is an areal measure for the entire basin, the adjustment of isopleth spacing and hence the area of each runoff zone within the basin was used to obtain a value of estimated runoff, matching the observed one. The adjustment of isopleth-spacing was performed with considerations of topography and climate. It was a time-consuming task to adjust the isopleth spacing, calculate the zonal contribution to total basin runoff and at the same time consider topographic and climatic effects. Because of the linear relationship between the readings on the planimeter scale and the zonal runoff, it was therefore possible to construct nomograms (as convenience diagrams) to facilitate

the adjustment of isopleth spacing. See Figure 4.1.

In the drawing of isopleths, a gradient pattern was assumed to exist between the Cypress Hills plateau and the surrounding plains. This can easily be justified for it is obvious that greater water surplus can be obtained from the higher level sites. The question remains: How far from the plateau can the gradient pattern be extended? In the absence of more data points, it was assumed that the gradient pattern extended as far as the outermost limits of the study area. This is likely to be not true and has to be clarified by later results. The resulting isopleth patterns are shown in Figure 4.2 to Figure 4.5, which consist of four water surplus maps representing each of the form calendar years covered by the study period.

4.5 The Surplus Isopleths

It was not possible to draw in the surplus isopleths for some of the basins due to the lack of sufficient data points. However, the general pattern of the surplus isopleths is still readily observable. There are several interesting aspects indicated by the isopleth maps:

4.5.1 The Gradient Pattern

Within the study area, the gradient pattern of water surplus can probably hold only for the immediate vicinity of the Cypress Hills plateau. It was not possible to estimate

FIGURE 4 :1

PLANIMETER READING - DISCHARGE CONTRIBUTION RELATIONSHIP

Battle Creek at Ranger Station

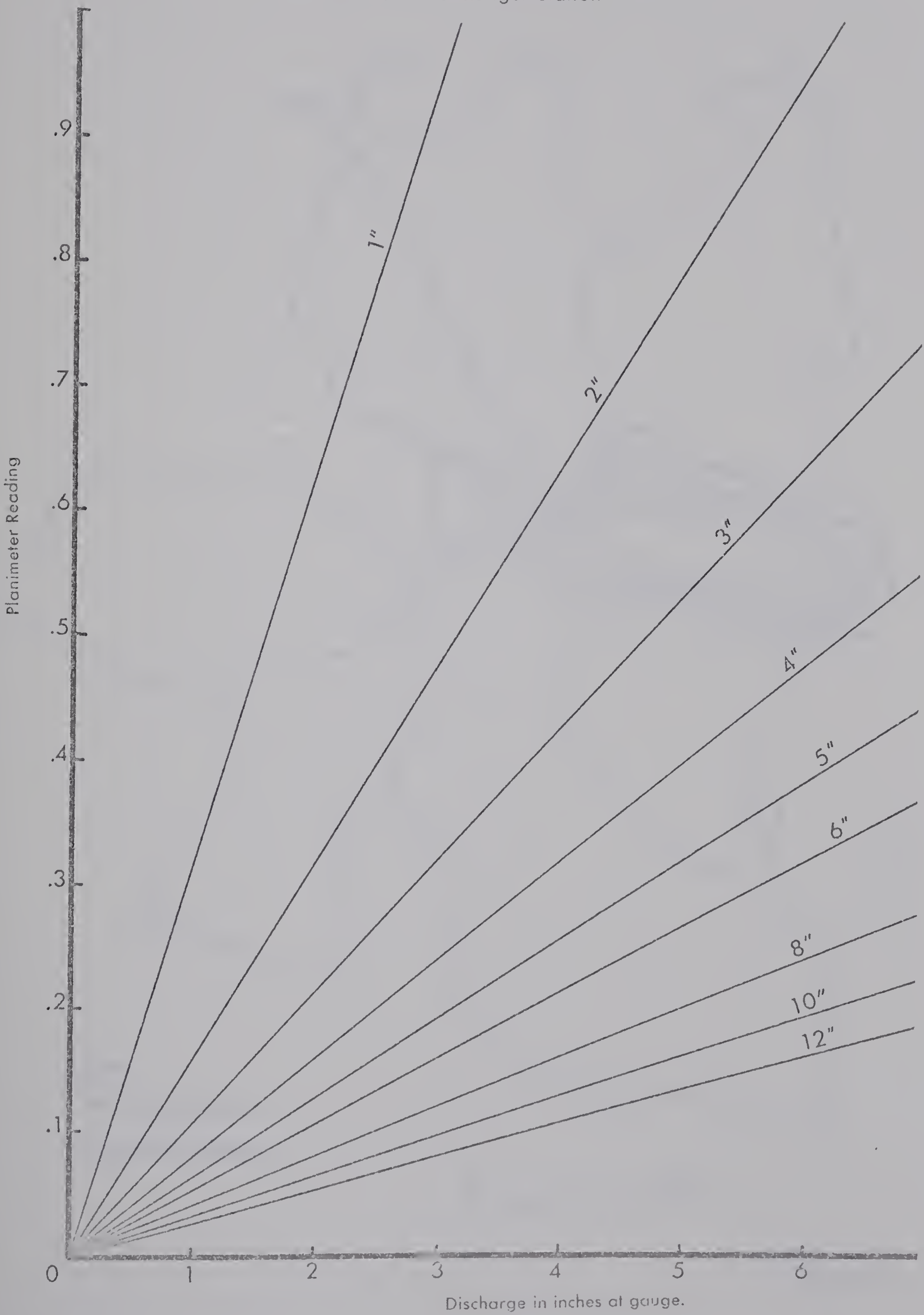


FIGURE 4:2

WATER SURPLUS PATTERN 1968

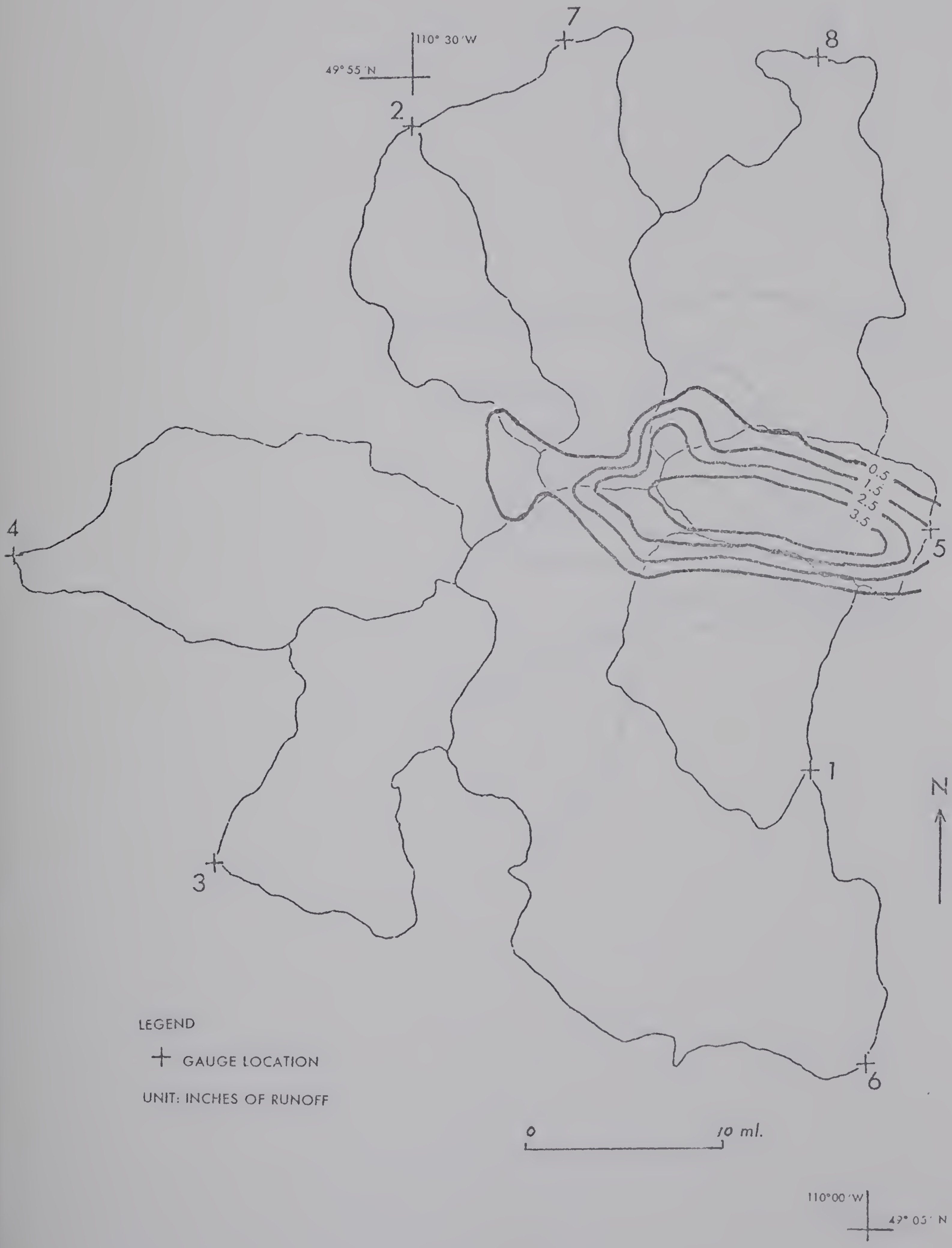


FIGURE 4:3

WATER SURPLUS PATTERN 1969

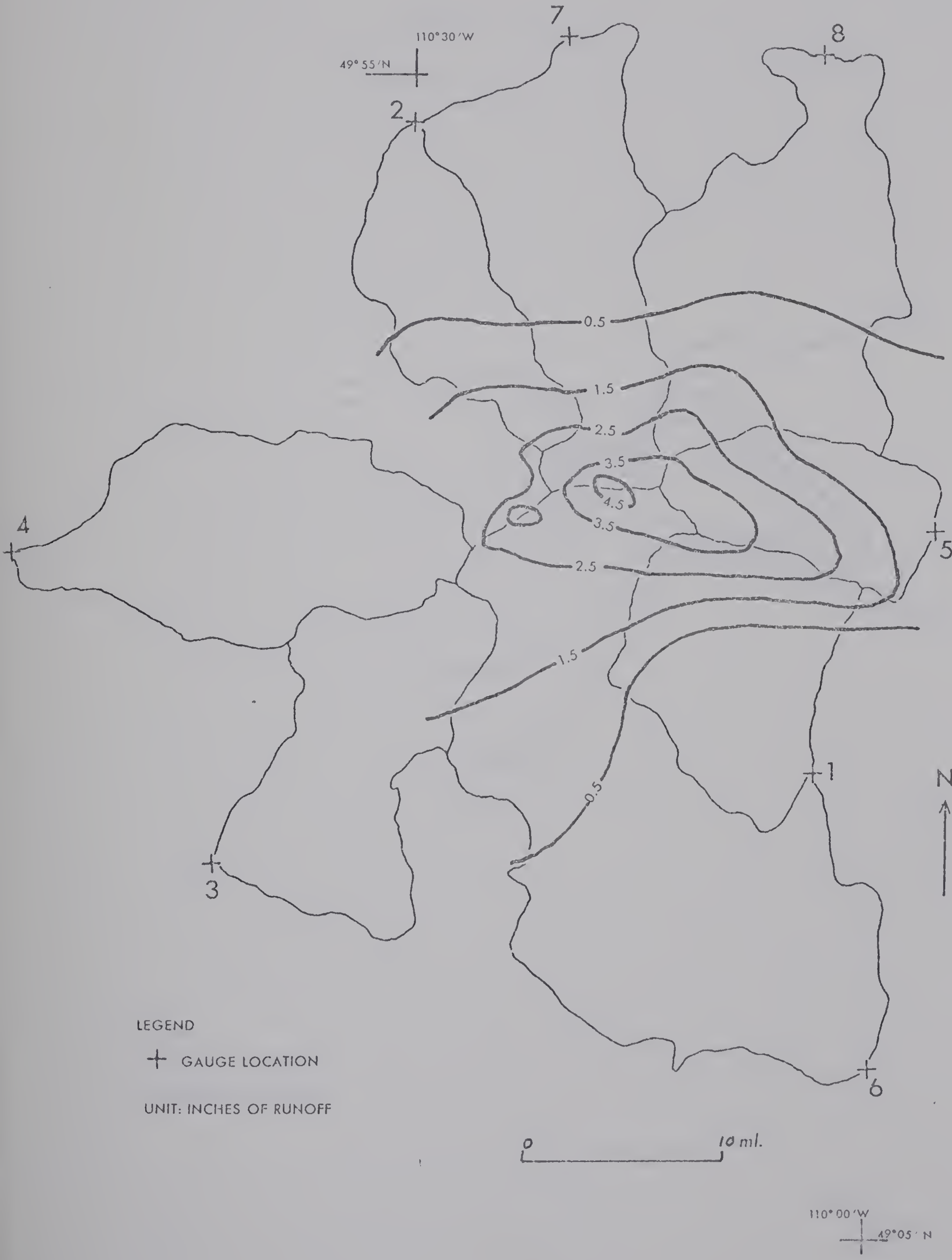


FIGURE 4:4

WATER SURPLUS PATTERN 1970

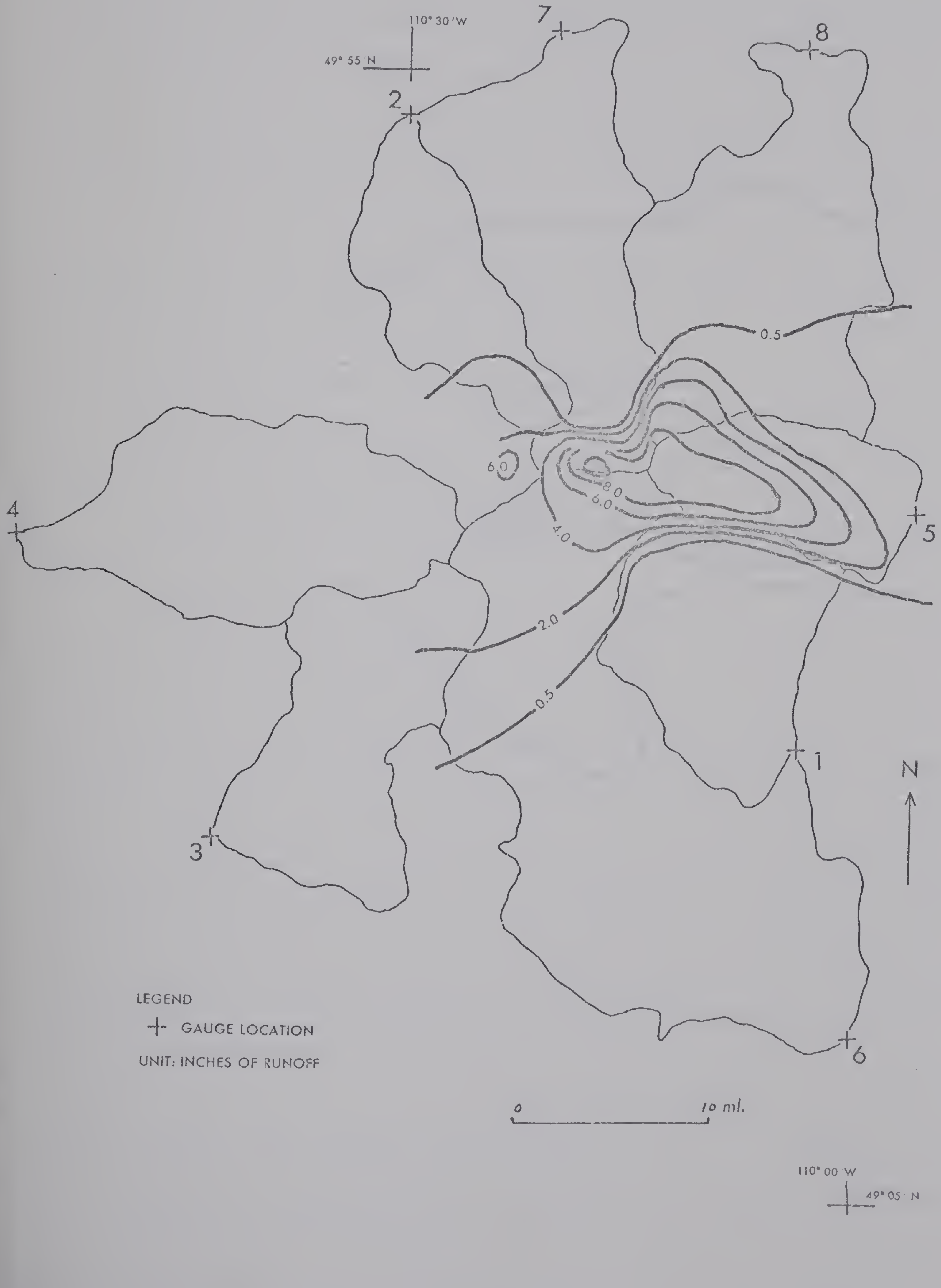
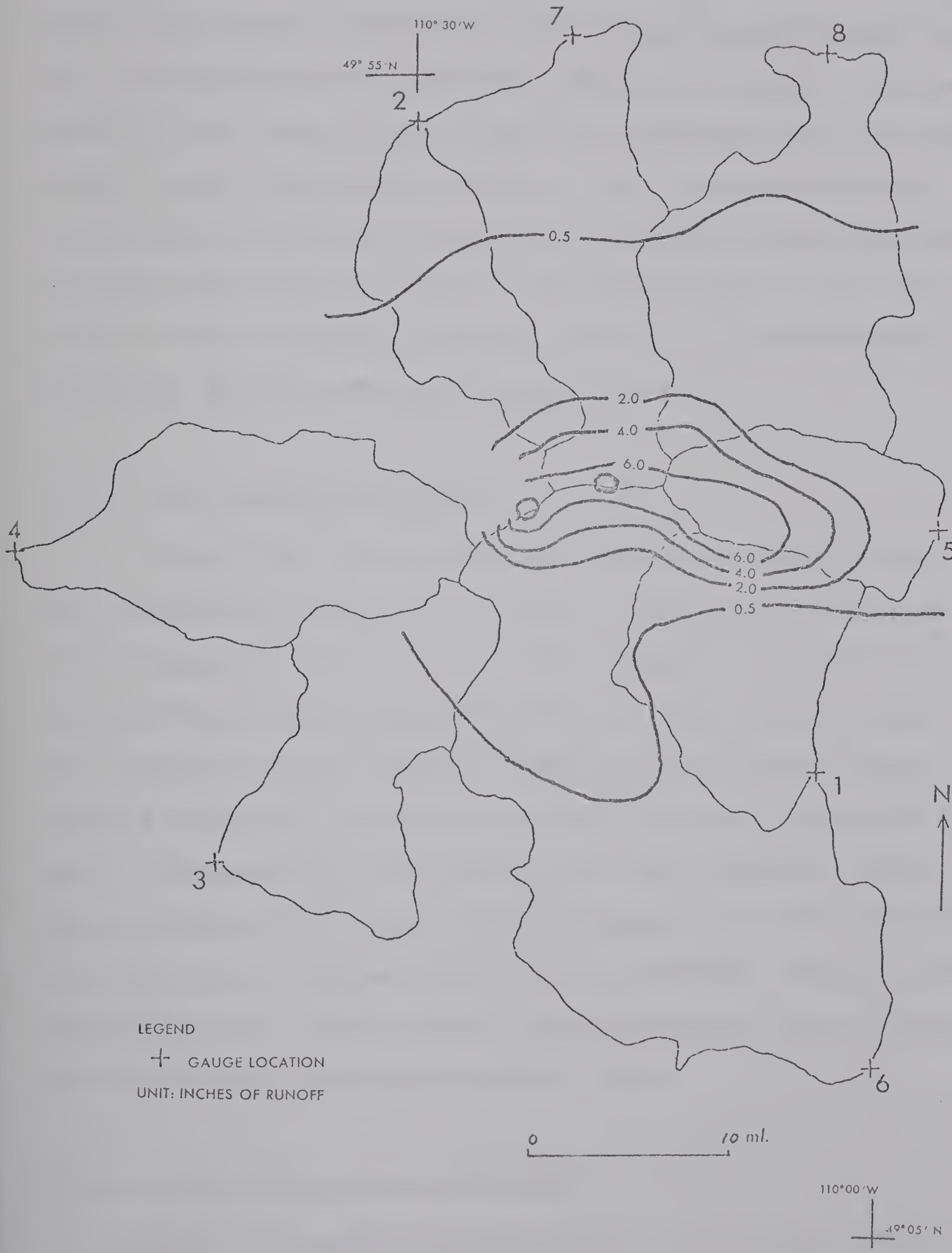


FIGURE 4:5

WATER SURPLUS PATTERN 1971



what the pattern would be beyond this area due to the lack of stations. But the presence of the nested basins of Gauge 2 and Gauge 7, i.e. Gros Ventre Creek near Dunmore and Ross Creek near Irvine respectively did allow the examination into the continuation of the gradient pattern of runoff. In some years, it was impossible to match the observed runoff at both gauges using the gradient pattern. This suggested that at least within the Gauge 7 basin, i.e. the Ross Creek basin which includes the drainage area of Gros Ventre Creek, some other factors than topography might be operative in predominantly affecting the distribution of water yield.

4.5.2 The Rainshadow Effect

Except for the comparatively dry year of 1968, there was a pronounced bend in the surplus isopleths to the south of the Cypress Hills plateau. This suggests a probable rainshadow effect which the Cypress Hills plateau imposed upon the pattern of water surplus. The prevailing storm track brought cold front precipitation from the north and northwest. Consequently, the southern and south-eastern slopes of the Cypress Hills was in the rainshadow. In the drier year of 1968, the rainshadow effect was not distinct enough to be depicted by the present sparce station network, but it becomes more conspicuous during the wetter years.

4.5.3 A Wet Year versus a Dry Year

1968 was a comparatively dry year, the surplus pattern of

which can be compared with that of 1971 which is comparatively wet. It is indicated that in 1971, there was a greater surplus area extending outward from the Cypress Hills plateau and the gradient of surplus isopleths was greater, particularly along the plateau slopes. These were accompanied by a greater increase in measured runoff for the basins having large areas within the low level plains than for the Gauge 5 basin, i.e. Battle Creek at Ranger Station, which occupied a higher level location. The rainshadow effect was more pronounced. It must be stressed that these are only suggested patterns. Only preliminary conclusions are to be drawn. They are acceptable suggestions because they are generally in agreement with patterns based upon hydrometeorological principles. More data collection is needed for further substantiation of their status.

4.6 The Mapping Problem

The difficulty caused by sparse station network in describing the gradient surplus pattern was mentioned in Section 4.5.1. In the cases of Gauge 3 and Gauge 4 basins, i.e. Manyberries Creek at Brodin's Farm and Peigan Creek near Pakowki Road respectively, the drawing of isopleths was impossible because of the lack of meteorological stations near or within the relatively large basin areas. It was not reasonable to extrapolate from the water balance conditions of the North Prairie site (Station 7) or the South Prairie site (Station 8) or to depict the pattern based on runoff alone, especially

after the indication that the gradient pattern might not hold beyond the immediate vicinities of the Cypress Hills plateau. Although there were a number of climatological stations within the surrounding plains which may help to increase the station network density, the records at these stations were not continuous enough to allow meaningful estimation of water surplus.

Based on the available information, the surplus-producing zone of each drainage basin was limited to a small area near the Cypress Hills plateau, especially in cases where the observed runoff was low. e.g. Gauge 7 in 1968 and 1970; all gauges in 1968. Very little can be said about the water balance conditions in the vast portions of low level basin area.

Some of the meteorological sites had sheltered locations. For instance, Station 2 and Station 5 were set up in forested areas while Station 6 was located in the bottom of a coulee. The water balance conditions of such stations may vary considerably from those of nearby stations with more open environments, situated only a short distance away. This means an accentuation of the spatial variation of water balance conditions, bringing out the odd details of the pattern, which would otherwise be smoothed out.

CHAPTER V

THE REGRESSION MODELS AND THE TIME LAG FACTOR

> Every theory of the course of events in nature is necessarily based on some process of simplication and is to some extent, therefore, a fairy tale.
>
> \- Sir Napier Shaw

5.1 Introduction

Models are epitomes of theories, and regression models in particular, are in many ways 'fairy tales' because they are great simplifications of the theories behind the natural phenomena they are trying to describe. By using a regression model, one is able to express the relationships between the dependent and independent variables or the comparative importance among the independent variables in terms of real number coefficients. If the relationships are stable and significant, regression models may be used for prediction purposes.

Regression analyses were performed using both annual values and daily values of the variables concerned.

The mean spring temperature and total winter precipitation as measured at the meteorological stations were related to the total spring discharge and the time span of the rising limb of the annual hydrograph. There were difficulties in obtaining significant relationships when the mean annual values were used because of the small number of observations. Testing of the models by using the last year of the available data did not produce satisfactory results.

Significant regressions were obtained by using the daily values of meteorological parameters. No daily precipitation data were available, and temperature variables were used. Most of the regression models failed when they were tested using the 1972 data. This indicated the instability of the relationships. Without further improvements, the models are unfit for prediction purposes.

It was found that in the comparatively dry year of 1968, the peaks in degree-days from 32°F preceded the local peaks in the discharge hydrograph. The time lag between them was three days for the Lodge Creek Basin. Further investigation into the time lag factor is recommended.

5.2 The Estimation of Seasonal Runoff Using Annual Values

Two regression analyses were performed for each hydrometric station , with the aim of finding some kind of statistical relationship between runoff and the meteorological controls.

5.2.1 The 1972 Data for Model Testing

It is necessary to specify again at this stage that not all available records will be used for model formulation. The meteorological and hydrometric records of 1972 are to be set aside for testing purposes. The usefulness of the regression models will depend on how closely the predicted runoff

related to the observed runoff. It is recognized that such a testing method is crude. Ideally, the models should be tested over a number of years. However, data deficiency in the present study precludes such a procedure.

5.2.2 The Dependent Variables

The dependent variables, or predictands used are (1) spring runoff (Y_1) and (2) the time of peak flow occurrence (Y_2). Spring runoff is defined here as the total runoff from February to May in inches, and the time of peak flow occurrence (Y_2) is defined here as the number of days since melting when peak discharge occurred. The definition of these two dependent variables requires some justification. The runoff from February to May is essentially snowmelt runoff. Significant snowmelt runoff rarely occurred in February, but there were odd instances during the study period when discharge was recorded at the end of February. These values were included. The peak of snowmelt runoff occurred usually in March or April, and in no instances did it occur after May. In most cases, the general tendency of discharge in May was that of recession flow. Hence the total discharge from February to May constitute a considerable portion, if not all, of spring snowmelt runoff. As a dependent variable in a regression analysis, it probably relates well to such meteorological controls as total winter precipitation and mean spring temperature.

The second dependent variable selected for regression

analysis is an expression of the occurrence time of peak discharge in terms of the period of the rising limb. Melting was considered to have begun on the first day of non-zero discharge, which was also the starting point of the rising limb of the discharge hydrograph. Peak discharge was taken as the maximum daily discharge recorded. It was expected that this dependent variable should relate well to the mean spring temperature, which is a surrogate for the quantity of available energy for melting.

The selection of these two variables were intended to be only preliminary. If significant relationships were found, further dependent variables would be added in an attempt to provide a more complete picture of the relationships.

5.2.3 The Independent Variables

There were twenty independent variables representing the mean spring temperature and total winter precipitation for each of the ten meteorological stations involved. The stations included the eight meteorological sites originally selected, Manyberries CDA and Medicine Hat. The mean spring temperature was defined as the average temperature from March to May, and the total winter precipitation was defined as the total amount of precipitation from October to the following April. It was expected that these two parameters were significantly related to the nature of spring snowmelt runoff, and regression models might be developed from these. However, in

the analysis, only those meteorological stations, the records of which were likely to be related to the discharge at the gauge sites, were selected. For instance, it was not expected that the discharge at Gauge 7, Ross Creek near Irvine would be well related to the meteorological records at the South Prairie site. Consequently, the records of the South Prairie site were excluded in the considerations of relationships with the Ross Creek discharge.

5.2.4 The Limitations of a Small Sample Size

There were a total of five years of meteorological records at the eight meteorological sites. When the last year of record was set aside for testing purposes, the actual sample size of meteorological records for model formulation was reduced to four years. This means that for each of the independent and dependent variables, four observations are to be used in the analyses. From the hydrometeorological viewpoint, the general representativeness of such a sample can be doubted because wet and dry years tend to cluster together along a hydrometeorological time series, and the regression models obtained from such a short period would probably need checking from time to time to ensure the stability of the relationships. Statistically, a sample of four means that the maximum number of independent variables to be included in the regression model can only be two. This is due to the partitioning of the total degrees of freedom. The linear regression equation with two independent variables is the equation

of a plane which in the case of the present study was to be fitted through four points in the observational space. Significant relationships could only be established with minimal deviation of the points from the regression plane.

Due to the small sample size, conclusions could not be drawn with respect to the frequency distribution of the observations, nor was it possible to apply orthogonalization techniques. Here the power of regression analysis as an analytical tool was reduced to one for curve-fitting only.

5.2.5 The Results

Only four of the original eight hydrometric stations were found to have significant relationships between their spring snowmelt runoff and the variables representing meteorological controls. The significant regression models are shown in Table 5.1. But the level of significance varies from the undesirable 25% to the good 2.5%. Only eight regression equations meet the 10% significance requirement, which was one of the original goals. There is no distinguishable pattern as to which independent variable is related to a particular dependent variable. Since only temperature and precipitation variables were included, both selected independent variables were involved in determining discharge quantity and occurrence time of peak flow. It can be observed that the F values of the various

TABLE 5.1

REGRESSION MODELS USING ANNUAL DATA

GAUGE	DEP. VAR.	INTERCEPT	REGRESSION COEFFICIENT & INDEP. VAR. 1	REGRESSION COEFFICIENT & INDEP. VAR. 2	F
1	Y_1	15.69	$-0.32X_8$	$-0.25X_{12}$	33.55
	Y_1	15.66	$-0.32X_8$	$-0.34X_{15}$	34.31
	Y_2	55.07	$-14.99X_8$	$15.32X_2$	788.06*
2	Y_2	-169.53	$-0.39X_{10}$	$47.71X_{20}$	6728.77*
	Y_2	-188.21	$49.06X_{20}$	$-0.34X_{14}$	1017.15*
3	Y_1	5.5	$-0.33X_9$	$0.23X_2$	316.05*
	Y_2	118.13	$6.64X_3$	$-8.69X_7$	10.39
	Y_2	232.82	$-5.5X_9$	$-1.11X_{19}$	31.45
	Y_2	226.2	$-5.7X_9$	$0.27X_2$	14.74
4	Y_1	3.94	$-0.25X_9$	$0.2X_2$	6.12
5	Y_1	19.56	$0.48X_1$	$-0.99X_2$	18.55
7	Y_1	-1.42	$0.03X_3$	$0.94X_{26}$	138.78*
	Y_1	-1.65	$0.04X_7$	$0.97X_{26}$	458.82*
	Y_1	-1.66	$0.04X_4$	$0.93X_{26}$	14435.20*
	Y_2	252.59	$-7.5X_7$	$20.18X_{17}$	69.70*

Gauge 6 & 8 had no significant relationships identified.
The relationships shown are significant at 25% or less. Significant relationships at 10% or less are marked with an asterisk.

-continued on next page

Y_1 = Total Spring Discharge

Y_2 = Number of days since melting when peak occurs.

Legend for independent variables:

	Mean Spring Temperature	Total Winter Precipitation
Stn 1	X_1	X_{11}
2	X_2	X_{12}
3	X_3	X_{13}
4	X_4	X_{14}
5	X_5	X_{15}
6	X_6	X_{16}
7	X_7	X_{17}
8	X_8	X_{18}
Manyberries	X_9	X_{19}
Medicine Hat	X_{10}	X_{20}

X_{26} = Discharge (total Spring Discharge Feb. - May) at Gauge 2

regression models have a very wide range. This shows that either the data points are very close to the regression plane, or very far from it. Since there are only four points used in fixing the regression plane, the cause for such difference in F values may very well be random. There are also cases where the regression coefficient of one independent variable is much greater than the other. These are indications that one is more related to the dependent variable than the other, e.g. the Gauge 7 total spring discharge is more related to Gauge 2 total spring discharge than the temperature conditions of Station 3, 7 or 4.

The Gauge 7 basin (Ross Creek near Irvine), within which the Gauge 2 basin (Gros Ventre Creek near Dunmore) was nested is again presented as an interesting case. While there were no significant relationships found in the case of Gauge 2 (Gros Ventre Creek near Dunmore) for discharge volume prediction, the actual measured discharge at Gauge 2 was likely to be a powerful prediction for the discharge at Gauge 7. High statistical significance was attained whenever the variable was included. Under the present data availability conditions, regression analysis is likely to work better in the correlative association of discharge characteristics among stream gauges, even where the basins are not nested.

Considerable differences between the predicted values and

and the observed values were found when the models were put into test . Even the more significant regression models were not found to be functioning tools for the purpose of prediction and in some cases, impossible or highly improbable values occurred. An obvious explanation is again the lack of sufficient data points. The condition can easily be visualized when one considers that in the analyses, the positions of the regression planes were determined by four points in space. The fifth point was then used to test the usefulness of the regression plane as a tool for prediction. To expect a fifth point to fall on a plane fitted with four points is far more difficult than to expect, say, a tenth point to fall on a plane fitted by nine points. If the data sample size was larger, the regression models could be expected to be more generalized and the likelihood of it being a useful forecasting tool would be increased. Larger sample means longer period of record. The longer the record the more representative the regression equation will be. More successful models can then be obtained. Although predictions based on the present models are not practicable, the models as they stand do provide encouraging indications that better models along these lines are possible with longer records. 1972 is probably a bad year for model testing in terms of precipitation and temperature conditions. A more "average" year is probably better for testing models developed from such a short period of record. ("Average is defined with respect to the available period of record

concerned). However, there is little choice at present because of data deficiency.

5.3 The Estimation of Seasonal Runoff Using Daily Values

By resorting to the daily meteorological observations for analysis purposes, it is possible to increase the number of available observations and to find out if the daily values reveal better any relationships between atmospheric conditions and runoff.

5.3.1 The Limitations of Using Daily Values

There were several problems when the daily values were to be used for analysis. The greatest difficulty was the absence of the daily precipitation records. It was unreasonable to attempt the estimation of daily values of precipitation because of the lack of suitable basis and the great variability of daily precipitation.

The variables that were to be used in the analysis were essentially temperature variables. These variables had comparatively continuous daily records. However, temperature conditions could at best represent only certain atmospheric conditions relating to evapotranspiration rate. e.g. humidity. Although evapotranspiration was known to be related to streamflow,

the relationship between temperature and streamflow, especially on a daily basis, was still to be investigated for the study area.

Orthogonalization techniques were not used because it was intended to keep the predictors as simple as possible. Also, since only temperature variables were involved, it was not expected that any orthogonal factors or principal components identified would have significant meaning as far as interpretation was concerned. For example, a linear combination of daily and dewpoint temperature would be more difficult to interpret than a single variable representing certain atmospheric conditions. The regression analyses used in the present study were not stepwise regressions, where a variable would be added or deleted according to its contribution to the regression. In such cases, the independence of each predictor must be observed otherwise the regression coefficients of the variables would change with the addition or deletion of a variable. In the present study, nine independent variables were used in each case, representing three meteorological stations. Interdependence amongst the selected predictors was assumed to be the same at all times.

5.3.2 Frequency Distribution and Transformation

With a larger sample, it is possible to examine the nature of the frequency distributions of the variables.

Temperature data were found to be fairly normally distributed. But the discharge data, as expected, were very skewed. It was therefore necessary to apply a transformation to the discharge data. All discharge data were transformed logarithmically and the regression analyses done after transformation were found to give much better results. The transformation was to be incorporated into the resulting models.

5.3.3 The Dependent Variable

The dependent variable selected was the daily measured discharge in c.f.s., transformed by taking the common logarithm of the actual values. The period during which the analyses were performed was from March to June of each of the first four years. This should include the major portion of the annual discharge hydrograph, and be able to avoid the presence of excessive number of zero discharge values which might seriously affect the slope of the regression surface. The 1972 data were again reserved for testing purposes.

5.3.4 The Independent Variables

For each meteorological stations selected, three independent variables were used, one representing daily temperature and two representing atmospheric humidity. Daily temperature was estimated by the equation

$$\bar{T} = \tfrac{1}{2}\,(Tmax + Tmin)$$

Where: $\bar{T}$ is the mean daily temperature
Tmax is the daily maximum temperature
Tmin is the daily minimum temperature

Atmospheric humidity was represented by the dew point temperature and the "dew point depression". The available daily records of the sling psychrometer were entered in terms of dry bulb temperature and dew point temperature. Similar to the wet bulb depression, the difference between the dry bulb temperature and the dew point is defined here as the "dew point depression", which is, in part, a function of the humidity condition of the air. The dew point depression is approximately two times the wet bulb depression (Fairbridge, 1964, p. 1137). Three stations were selected for each dependent variable to introduce a spatial element into the regression model. The choice of stations was again based on probable relationship between the station and the drainage basin involved.

It was intended that the selection was to be preliminary. Further independent variables may be added if significant relationships were found. Thornthwaite's water balance method described earlier involves an estimation of potential evapotranspiration using mean temperature alone. The choice of mean daily temperature here was based on the same principle. It was used as an indicator of the amount of potential evapotranspiration.

The dew point temperature is the temperature to which the air must be cooled isobarically and with constant water vapour content, in order to reach saturation. It is, therefore, a function of atmospheric pressure and the relative humidity.

The quantity of moisture in the air is a function of the amount of actual evapotranspiration which has taken place 'in situ' and the amount of moisture which has been advectively transported. The humidity of the air is also an indicator of the saturation deficit, or the potential of the air to take up more water vapour under the prevailing conditions. Since dew point is in part a function of humidity, it represents a partial measure of evapotranspiration conditions. It is recognized that any relationship detected between dew point and runoff will not have a good theoretical base. But in the absence of other more appropriate variables, it may be a worthwhile statistical exercise to have its inclusion.

Once again, in the case of Gauge 7, Ross Creek near Irvine, the discharge measured at Gauge 2, Gros Ventre Creek near Dunmore, was used as a predictor together with meteorological variables.

5.3.5 The Results

The results of the analyses are presented in Table 5.2.

TABLE 5.2

REGRESSION MODELS USING DAILY DATA

Gauge 1.

$$\log Y = 2.33+0.06X_{11}-0.04X_{13}-0.03X_{21}+0.03X_{22}-0.02X_{23}$$
$$+0.0.X_{81}-0.09X_{82}+0.02X_{83}$$

$F = 3.42^{*}$ d.f. = 9,234 $r = -0.01$

Gauge 2.

$$\log Y = 2.41-0.04X_{21}-0.03X_{22}-0.02X_{23}-0.03X_{62}-0.04X_{63}$$
$$+0.09X_{71}-0.05X_{72}+0.01X_{73}$$

$F = 12.11^{*}$ d.f. = 9,244 $r = -0.1$

Gauge 3.

$$\log Y = -1.21-0.1X_{11}-0.13X_{12}-0.14X_{13}+0.04X_{41}+0.02X_{42}$$
$$+0.05X_{43}+0.08X_{81}+0.08X_{82}+0.05X_{83}$$

$F = 1.689$ d.f. = 9,64 Test Not Possible

Gauge 4.

$$\log Y = 3.25-0.11X_{11}-0.02X_{12}-0.05X_{13}+0.02X_{41}-0.05X_{42}$$
$$+0.1X_{71}-0.01X_{72}$$

$F = 11.067^{*}$ d.f. = 9,227 $r = 0.4$

Gauge 5.

$$\log Y = 3.12+0.03X_{11}-0.01X_{12}-0.03X_{13}-0.06X_{21}-0.01X_{22}$$
$$-0.02X_{23}+0.08X_{31}-0.03X_{32}$$

$F = 2.027^{**}$ d.f. = 9,240 $r = 0.11$

- continued on next page.

Gauge 6.

$$\log Y = 3.63-0.12X_{21}-0.06X_{23}+0.18X_{31}-0.03X_{32}-0.02X_{33}$$
$$-0.06X_{81}-0.01X_{82}+0.06X_{83}$$

$F = 3.3*$ d.f. = 9,242 $r = 0.26$

Gauge 7.

$$Y = 10.14-0.21X_{11}-0.09X_{12}-0.05X_{13}+0.07X_{21}+0.13X_{22}+0.07X_{23}$$
$$+1.21X_{24}-0.03X_{73}$$

$F = 47.99*$ d.f. = 9,223 $r = 0.95$

Gauge 8.

$$\log Y = 3.09-0.02X_{12}-0.02X_{13}-0.05X_{21}+0.04X_{22}+0.03X_{23}$$
$$+0.03X_{71}-0.05X_{72}-0.02X_{73}$$

$F = 3.548*$ d.f. = 9,223 $r = 0.01$

Where

Y = Discharge
Xij = Independent variables
i = stn number
j = variable number
1 = daily temperature
2 = daily dew point
3 = daily dew point depression
4 = discharge
F = Value of F for significance test
d.f. = degrees of freedom
r = product-moment correlation coefficient between observed and predicted runoff, using 1972 data.

* Significant at 1% level
** Signficant at 5% level

High statistical significance was obtained in all cases except Gauge 3, (Manyberries Creek at Brodins Farm), which barely made the 10% level. With only a few exceptions, the regression coefficients are invariably low. This is an indication that the individual independent variables are poorly related to the dependent variable. This is a point where statistics ends and common sense takes over. Although all of the selected variables together have given a significant regression, the relationship is unlikely to be stable enough for prediction purposes. When the 1972 data were used for testing of the models, the correlation coefficients between the observed and predicted runoff were low, with the exception of Gauge 7. (Ross Creek near Irvine). The regression equation for the discharge at the Ross Creek gauge has the Gauge 2 (Gros Ventre Creek near Dunmore) discharge as one of its predictors. The regression coefficient for this particular predictor is the highest (1.21), indicating a strong relationship. The regression equation as a whole also has the highest statistical significance. ($F = 47.99$, with 9 and 233 degrees of freedom).

The results indicate that the daily temperature data alone are inappropriate for use as predictors in runoff prediction models. Significant regressions may be obtained, but the models are not useful for prediction purposes.

5.4 A Graphical Interpretation

5.4.1 The Degree-day and Snowmelt Discharge

In a broad sense, the degree-day can be used to represent a measure of the available amount of heat at a point. When the reference temperature is taken to be 32°F, the degree-day total above 32°F may be used as an index for snowmelt. Bruce and Clark have indicated that within limits, the reference temperature selected is not of critical importance. (Bruce and Clark, 1966, p.258). Since the degree-day represents a heat index, its variation should relate to the daily variations in a snowmelt discharge hydrograph, no matter what the reference temperature might be. It has been indicated that the daily springtime snowmelt at a point may be estimated from degree-day values by simple correlation equations. (Chow, 1964, p.10-34).

5.4.2 Gauge 6, Lodge Creek, Spring Snowmelt Runoff, 1968

The usefulness of the degree-day as an index for daily discharge forecasting was examined by investigating the relationship between the spring snowmelt at Gauge 6, and the degree-day from 32°F at Station 2 (Summit Forest Site) and Station 8 (South Prairie Site). 1968 was selected because it was a comparatively dry year, during which discharge variation due to spring precipitation was likely to be minimal, and a

greater portion of the runoff variations may be attributed to temperature controls. Other years were checked and the best relationships were these of 1968.

Figures 5.1, 5.2 and 5.3 are used to illustrate the temporal variations of degree-day and discharge during the spring snowmelt period. Here, three meteorological stations are involved, viz, the North Prairie Site (Station 7), the South Prairie Site (Station 8) and the Summit Forest Site (Station 2). It is apparent that the patterns of degree-day variation among the stations are very similar. Since these stations represent different locations and environs, the similarity in degree-day patterns suggests that the general pattern of variation is likely to be representative of the basin under study, and there were few factors operative during the period concerned, in causing significant differences in patterns of temperature changes. While both are dealing with temperature-discharge relations, there are differences between this section of the study and the regression analysis of daily hydrometric and meteorological data. The chief concern of the study described in this section is the local changes along the reccession limb of the annual hydrograph. In addition to this, a time lag factor was involved.

5.4.3 The Time Lag

When a comparison is made between the discharge hydrograph

FIGURE 5:1

DEGREE - DAY PATTERN DURING SNOWMELT RUNOFF

STATION 7 1968

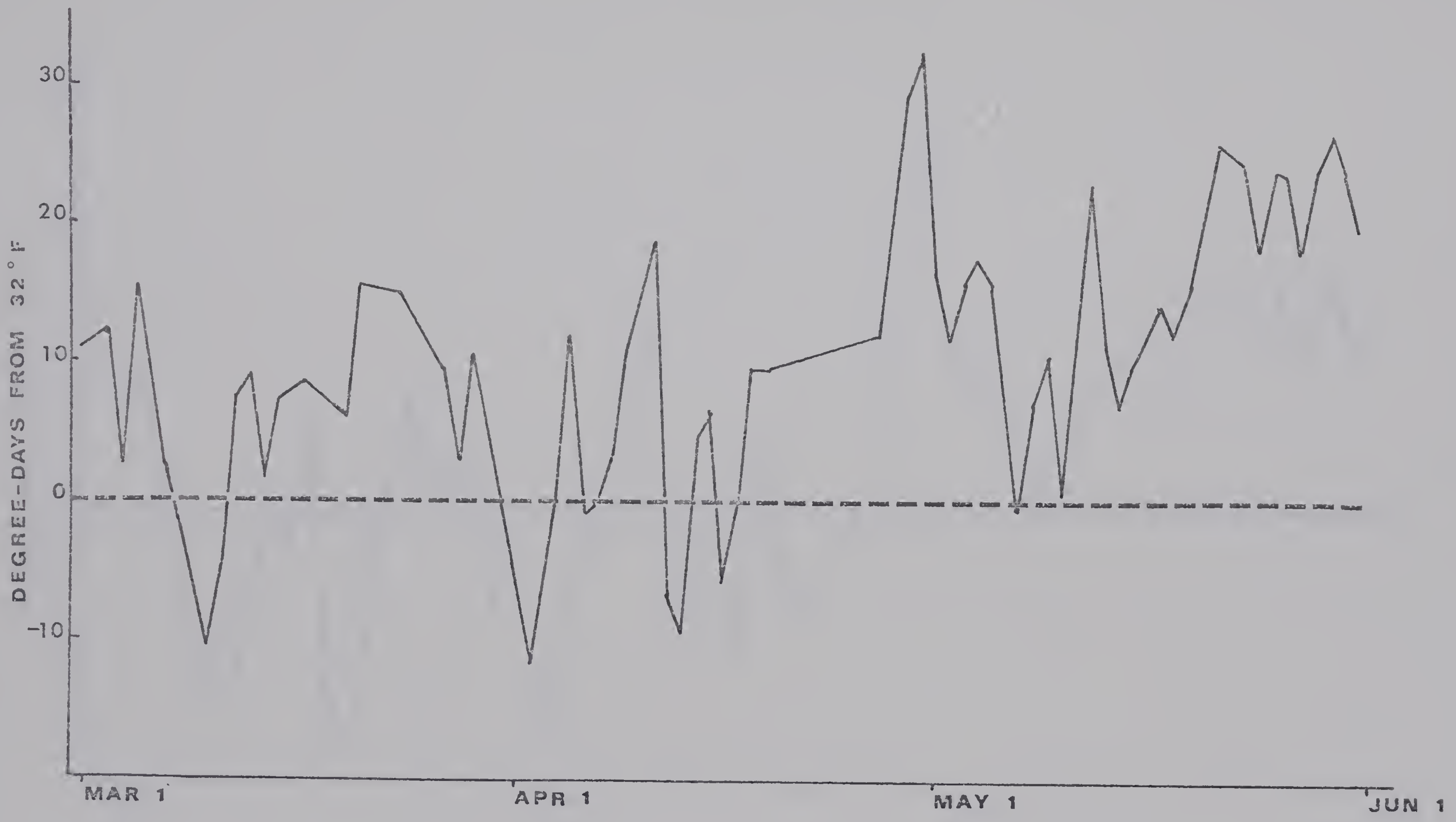


FIGURE 5:2

DEGREE - DAY PATTERN DURING SNOWMELT RUNOFF

STATION 2 1968

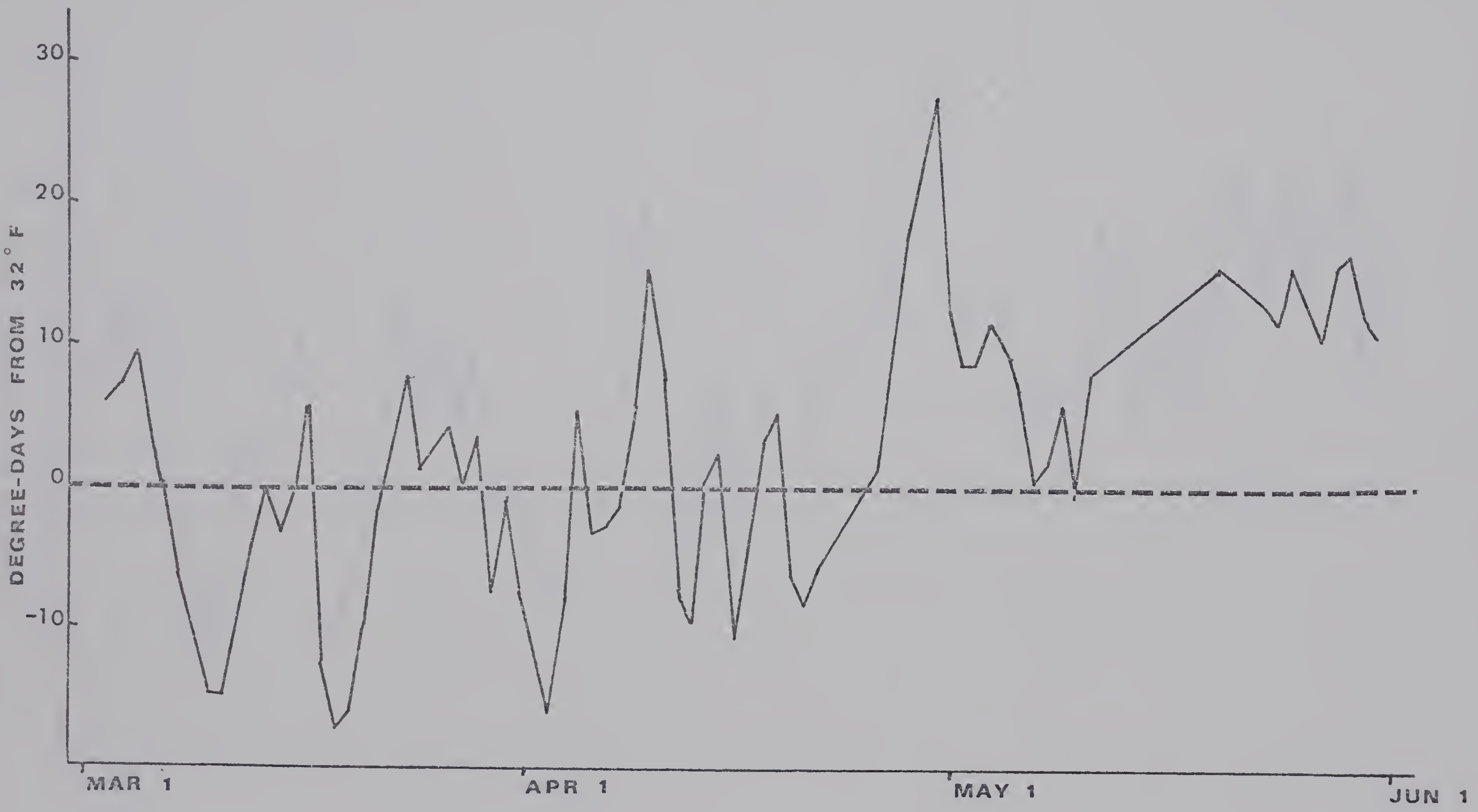
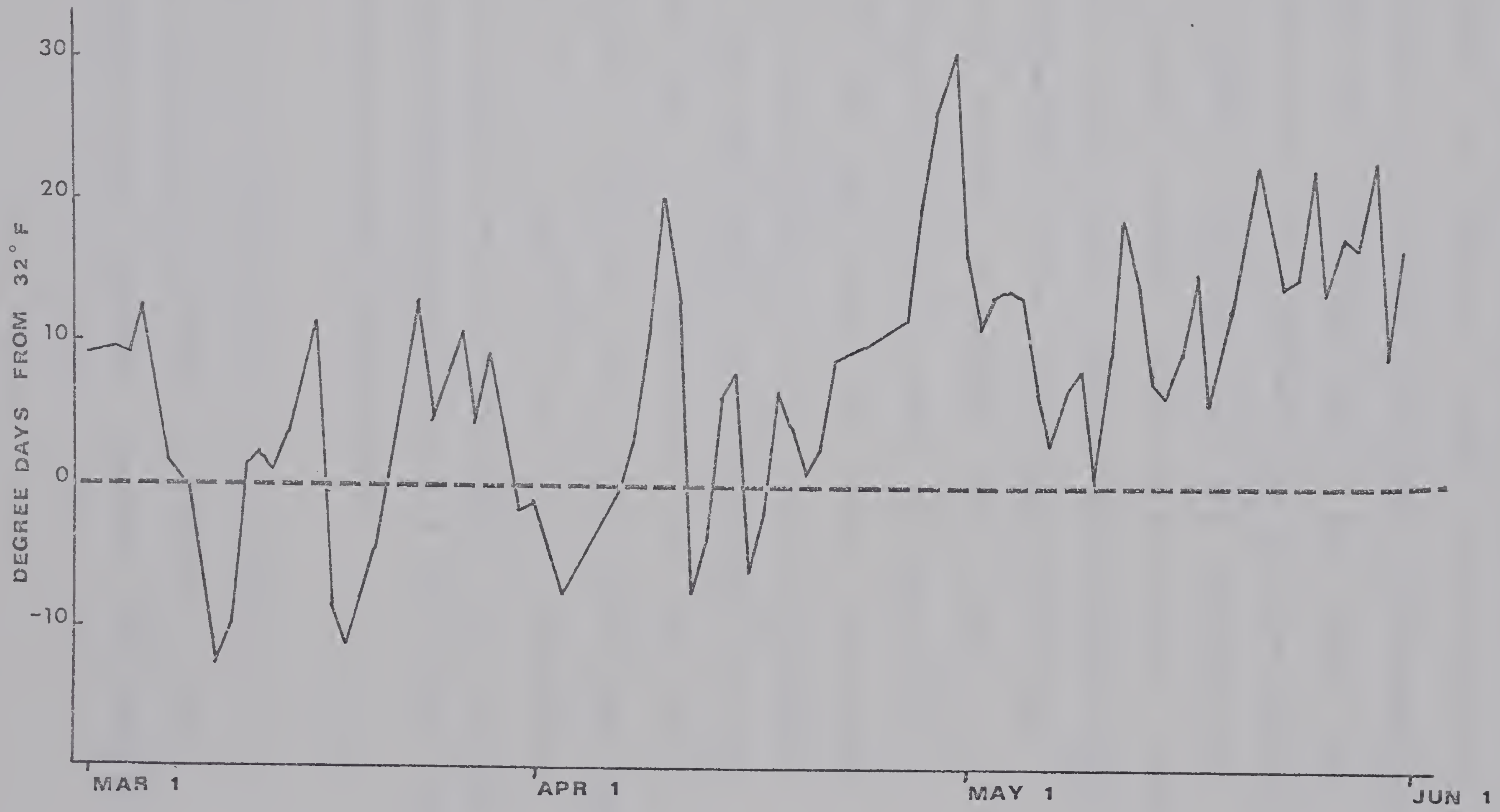


FIGURE 5:3

DEGREE - DAY PATTERN DURING SNOWMELT RUNOFF

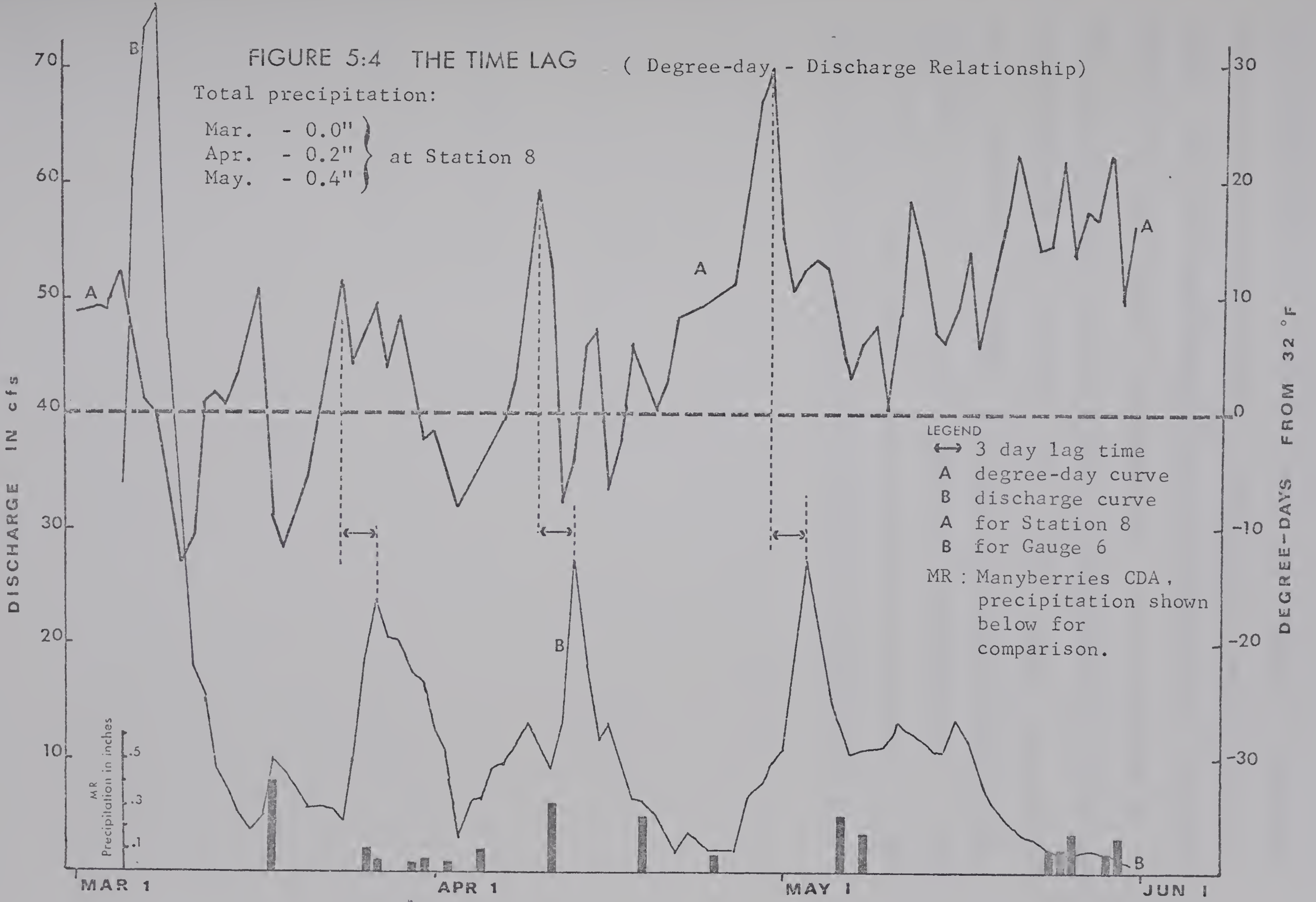
STATION 8 1968



and the degree-day pattern, It is readily observable that the patterns correspond fairly well but with a time lag. Here, the degree-day pattern at Station 8 (South Prairie Site) was used. Every secondary peak on the hydrograph was preceded by a temperature peak about three days ahead. (See Figure 5.4). This three day time lag may be considered as the time required for meltwater to travel to the gauge site via interflow and overland flow. There are various factors affecting the length of the time lag and these involve complex relationships which cannot be investigated due to the present data deficiency. Snow cover data, for example, if present, may be used in relating the time lag to the elevation where melting occurs. Since the same three day lag existed all through the melting season, it may be suggested that the snow cover within the Gauge 6 basin in 1967-1968 season was concentrated in a restricted high level zone. In a comparatively dry year, such a condition is extremely likely in a basin where lower level rain-shadow areas constitute a significant portion of the entire watershed. The available snow on ground records also indicate that the South Prairie meteorological site had very little snow accumulation throughout the 1967-1968 winter.

Without daily precipitation data, it is difficult to establish a general relationship between the quantity of discharge and the meteorological controls. However, the results

FIGURE 5:4 THE TIME LAG (Degree-day - Discharge Relationship)



do indicate that, at least in part, the timing of secondary peaks can be established by an analysis of temperature records. The introduction of the time lag leads to a new dimension in the present investigation: Is it possible to develop useful forecasting models by adjusting the time lag? By considering the three-day lag in the present case, statistical correlation between the degree-days and discharge was increased from -0.1 to 0.47, which was indicated by a t test to be highly significant. Much greater improvements in the results would be obtained with adequate precipitation data.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

In this chapter, the results of the present study are summarized. These include the water balance pattern and its variations, and the relationships between meteorological parameters and streamflow. It is expected that better results can be obtained by relocating the observational sites and maintaining continuous records. An alternative approach is also suggested for discharge-forecasting model formulation. However, this approach will not show any meteorological-hydrological relationships. A review of problems encountered is also included with suggestions for further research.

6.2 Major Results

The water balance conditions estimated by using the Thornthwaite procedure provided a basis for the production of water surplus maps. Data deficiencies were partly compensated for by estimates of winter precipitation values. The patterns identified were produced with the belief that the major characteristics of isoline trends has been adequately represented. The year to year variations of moisture conditions were reflected in the areal extent as well as the gradients of the surplus.

The surplus isolines were drawn under the assumption that a gradient pattern existed in the study area, with the highest water surplus area at the crest levels of the Cypress Hills plateau. It was found that the gradient pattern might not hold beyond the immediate vicinities of the plateau and more weather stations in the lower level plains area will be necessary if a more complete picture is to be produced.

The rainshadow effect was illustrated in the surplus isoline pattern. With the consideration that precipitation comes normally from the north and northwest, the area most affected by the rainshadow effect should lie to the south and southeast of the Cypress Hills plateau. The size of the area affected also changes with the moisture condition of the year. For example, during the study period, the expansion of the surplus zone on the northern and north-eastern slopes of the Cypress Hills plateau was not accompanied by a corresponding areal increase in the southern and south-eastern slopes.

Linear regression analyses using the existing meteorological and hydrological data did provide statistically significant relationships. But most relationships were found to be unsuitable for prediction purposes because of the low values of the regression coefficients, or instability due to insufficient data points.

It was found that temperature variables alone relate poorly to streamflow. Other parameters, particularly precipitation,have to be incorporated if meaningful relationships are to be found. However, in a comparatively dry year, streamflow variation was found to respond well with temperature change, if allowance was made for basin lag time. Investigation into the characteristics of this time lag factor will be an interesting exercise for future research.

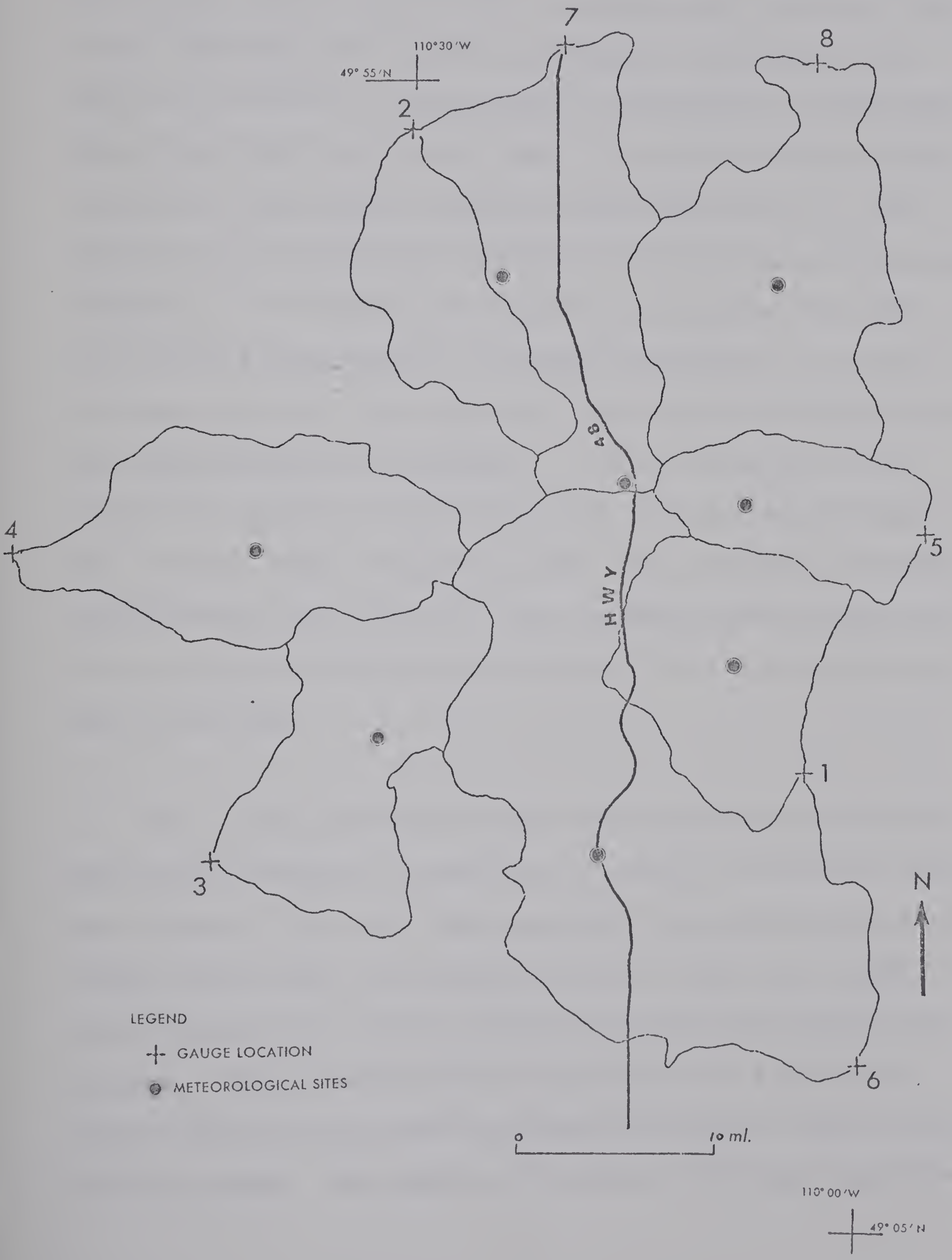
6.3 Recommendations

It is expected that significant improvements in the direction of better models and more accurate surplus patterns can be made with a more substantial data base, particularly in terms of more continuous and representative observations of winter precipitation conditions. The eight original meteorological sites were located with a different research problem than that of the present study in mind. (See section 2.8.1). Consequently, the distribution of stations was not exactly ideal for the present hydrometeorological investigation. A more representative distribution of meteorological sites is suggested in Figure 6.1. This proposed distribution involves the same number of stations, although more sites at the lower plains area would be desirable.

The relocation of meteorological stations is determined

FIGURE 6:1

PROPOSED LOCATIONS OF METEOROLOGICAL SITES.



so that each drainage basin is represented. Only one observational site is located at the crest level. Comparison of the observations at this station with the other lower plains stations will provide information relating to the spatial variation of meteorological conditions in different directions from the plateau core. The more or less central location of the plains stations within each basin is considered to be capable of providing fairly representative measurements. All stations are readily accessible by roads. No elaborate measurements of weather phenomena are needed at these stations, but recording instruments for temperature and precipitation are required. A more convenient alternative is a series of meteorological stations along Highway 48. In this case, it would be less time consuming in terms of monitoring the stations. The assumption that such a profile is representative of the Cypress Hills area would also have to be made.

It is also advisable to have more hydrometric stations monitoring streamflow conditions at various locations along each stream. This will make possible the subdivision of a larger basin into its component areas so that the runoff contribution from various sections of the basin can be calculated. Such results will make possible more detailed cross-checking with runoff estimates from the climatic water balance method. The absence of gauges in the more upstream

areas is a serious problem in the present model development.

More hydrometric stations along the stream will also allow more complete analysis of the groundwater balance conditions in various parts of the basin. This can be accomplished by hydrograph analysis. Although the long term net groundwater recharge within any sub-basin is likely to be zero, the short term changes still warrant investigation, especially with a spatial element involved.

6.4 The Hydrometric Approach

For the purpose of prediction, the streamflow time series may be analyzed, and a model based on autocorrelation may be formulated. All stream gauges involved in the present study have established discharge records and it is worthwhile to attempt time series analysis and explore the possibility of using the hydrometric approach in discharge forecasting. Such an approach does not have direct reference to the meteorological-hydrological relationships. So, while much less difficulty in terms of data availability may be expected in using such an approach for the present study, it is not considered as an appropriate choice. However, it is suggested that the hydrometric models may be used in supplementing the hydrometeorological ones. Further developments along this line may involve model testing by hydro-

metric methods. Predicted values from both approaches may be compared.

6.5 Model Stability

In the present study, the available data cover a period of five years, as far as the meteorological parameters are concerned. Any model developed within such a short span of time is subject to instability due to long term changes in climatic trends. Normally, a period of 30 years is considered acceptable as being representative. When such a long term record is not available, periodic updating of relationship models becomes necessary. Models are also subject to change due to environmental modification by human activities. Consideration of such changes is also necessary in order that a useful model for discharge forecasting is maintained.

Additional studies are needed for more effective relationship developments. Meanwhile, the experience of the present investigation is very valuable from the educational point of view.

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APPENDIX

THE ESTIMATION OF WINTER PRECIPITATION

(i) Introduction

It is necessary to estimate the winter precipitation at the meteorological sites before the water balance computation. The snowpack thickness data are not as useful as they can be because of the lack of snow density measurements. Continuous precipitation records from nearby stations are used in the estimation of winter precipitation at the meteorological sites and correlation coefficients are used in the association of stations. Satisfactory results were obtained by using two distribution ratios and an estimate of the 1967-1968 winter precipitation using snowpack thickness increments and a 10:1 conversion factor. Better precipitation records would still be preferable, but since these are lacking, the estimated values become the best substitutes.

(ii) The Usefulness of the Snowpack Thickness Data

With a reasonable amount of snow density information, the snowpack thickness data may be used in estimating the water equivalent of winter precipitation, in terms of both quantity and variability. It is also possible to estimate the potential quantity of water available for spring snowmelt runoff. There is only a very limited amount of snow

density information within the study area. (See Chapter 2) Consequently, the snowpack thickness data as observed at the meteorological sites can only be used as indices in some estimation method.

It was found that the measurements of snow on ground during the study period had very little practical value in estimating winter precipitation at the meteorological sites. The ratios of the total winter precipitation of each individual year to the overall mean winter precipitation for the study period for both Manyberries CDA and Medicine Hat are shown in Table I. The average snowpack thickness as measured at the stations are also expressed in ratios to the overall mean for each of the five winters covered by the present study. It is found that while the general patterns of fluctuation are fairly close, the snowpack ratios tend to be slightly higher for the 1970-1971 winter and slightly lower for the 1971-1972 winter than the precipitation ratios. Therefore, if the total winter precipitation for the meteorlogical stations are generated using the snowpack thickness ratios as indices, overestimation of the 1970-1971 winter precipitation and underestimation of the 1971-1972 winter precipitation may probably result. It may be argued that the snowpack ratios involve high level stations, the precipitation regimes of which may be different from those of Medicine Hat and Manyberries CDA, which are essentially low

level observational sites. But the magnitude of such a difference is difficult to assess. Until further studies are carried out to this purpose, it is considered inappropriate to use the snowpack ratios alone as indices for estimating winter precipitation. Moreover, this has to be done under the assumption that the average snow density over the entire study area did not change significantly from one year to another. Justification for such an assumption is also difficult to make.

It was also found that the available snow survey data are not of much use by themselves in providing better estimates of the water equivalent of snowpack. Snow surveys were carried out towards the end of February or the beginning of March at Elkwater, Alberta and Cypress Park, Saskatchewan. The results of these surveys are indicated in the lower half of Table I. It is readily seen that the density values at both sites are closely correlated during the study period. Average snow density values were computed using these measurements and applied to the snowpack thickness values to obtain a measure of snowpack water equivalent. Ratios to the overall mean were again used for comparison purposes. (See Table I) Greater deviations from the precipitation ratios are the results. This is an indication that the density values used are not representative of the study area. Resort to some other information for estimating winter precipitation is needed.

TABLE I

PRECIPITATION, SNOW DEPTH AND SNOW DENSITY VARIABILITY DURING (1967 - 1972) STUDY PERIOD.

	1967-68 Winter	1968-69 Winter	1969-70 Winter	1970-71 Winter	1971-72 Winter
*Medicine Hat ppt.	0.94	0.80	1.08	1.12	1.06
*Manyberries CDA ppt.	0.94	0.91	0.83	1.28	1.04
*Snowpack depth(Avg)	0.99	0.81	1.15	1.44	0.77
Snow density ⊙(Elkwater)	0.40	0.20	0.29	0.23	0.17
⊙(Cypress Park)	0.48	0.28	0.33	0.31	0.22
(Average)	0.43	0.24	0.31	0.27	0.19
Water equivalent	1.40	0.64	1.16	1.30	0.50
(Using average snowpack depth and average density)					

*These are expressed as a ratio to the overall mean of the study period.

⊙These are snow course surveys carried out about March 1.

(iii) The Selection of Base Stations by Correlation Method

It is a common practice to estimate missing precipitation values by resorting to the continuous precipitation record of a nearby station (base station). The two nearby base stations with continuous precipitation records during the study period are Manyberries CDA and Medicine Hat. (See Chapter 2) It is necessary to decide which of the eight meteorological stations within the study area should be related to which of these two base stations for the purpose of estimating winter precipitation. The summer precipitation measurements at the eight stations were related to the summer precipitation measurements at both Manyberries CDA and Medicine Hat by simple product-moment correlation coefficients. (See Table II.) These were used as criteria in selecting the base station for seven of the stations, while Station 8, which correlated poorly with both stations, was assigned to Manyberries CDA on the basis of distance alone.

It can be seen from Table II that in a number of cases, the values of the correlation coefficients are comparatively small. But this does not mean that the relationships are poor. A number of t tests were performed and it was found that all of these correlation coefficients were statistically significant, with the exception of those involving Station 8. The level of significance used was 10%, but in many cases, statistical significance can also be obtained at a 5% level. This means that, with small probability of making error (type

TABLE II

CORRELATION MATRIX OF SUMMER PRECIPITATION

	Medicine Hat	Manyberries CDA
Station 1	0.4358	0.4182
Station 2	0.7042	0.6446
Station 3	0.7427	0.8127
Station 4	0.4916	0.5164
Station 5	0.6221	0.6075
Station 6	0.8298	0.7937
Station 7	0.5766	0.5868
Station 8	0.1341	0.1303

The value of the correlation coefficient determines the assignment of the stations, except station 8. Stations 1, 2, 5, and 6 will be associated with Medicine Hat record for estimation, and stations 3, 4, 7, 8 will be associated with Manyberries CDA record for estimation. Station 8 is assigned to Manyberries CDA because of distance.

I error 0.1 or 0.05), one can say that a linear relationship exists between the summer precipitation record of any one of Stations 1 to 7 and the summer precipitation record of either Manyberries CDA or Medicine Hat.

The summer precipitation record of Station 8 was found to be poorly correlated with the records of both Manyberries CDA and Medicine Hat. (0.1341 with Medicine Hat and 0.1303 with Manyberries CDA). This may be due to the fact that Station 8 was situated in a different hydrometeorological environment. It was sheltered in the leeward sides of the Cypress Hills plateau. The presence of rainshadow effects may be the major cause of the insignificant correlation.

(iv) The Method of Estimation

The present method was developed after several attempts using different approaches, and it was found to give the most realistic results.

(a) Two Ratios

Two groups of ratios are computed from the records of the base stations:

(1) The ratios indicating the distribution of total winter precipitation during the study period.

(2) The ratios indicating the distribution of monthly precipitation during each winter.

For the sake of convenience, the terms 'winter' and

'summer' are used in a loose sense. Summer represents the months May to September, when precipitation records for the eight meteorological sites are available, and winter represents the period from October until the following May. The ratios computed are shown in Table III.

(b) A Starting Point for Calculation

A starting point is needed for each station and the winter precipitation can be estimated using these ratios. The 1967-1968 winter precipitation and snowpack records are used for this purpose. This is the first year of record and the precipitation and snowpack data are comparatively good. The precipitation value for each month is obtained by summing the occasional readings of rainfall and snowfall, together with an estimate of precipitation based on the fluctuations of snowpack thickness when precipitation records are absent. An increment in the weekly reading of snowpack depth is considered a result of precipitation. The total increment in a month is converted to water equivalent value. It is assumed that no precipitation had fallen during periods of snowpack depth decrease. This is probably not true and underestimation of winter precipitation may result. However, the moisture condition of the 1967-1968 winter was slightly below average. when comparison was made to the overall mean of the study period. (See Table I, the Medicine Hat and Manyberries CDA precipitation ratios.) It is also expected that little precipitation would have occurred

TABLE III

PRECIPITATION DISTRIBUTION RATIOS FOR MANYBERRIES CDA (MR) AND MEDICINE HAT (MH)

Ratio 1 is the distribution ratio of the total winter precipitation throughout the study period.

Ratio 2 is the distribution ratio of monthly precipitation within each winter.

		1967-68	1968-69	1969-70	1970-71	1971-72
Ratio 1	MH	1.0	.85	1.15	1.19	1.13
	MR	1.0	.97	.88	1.36	1.11
Ratio 2	MH					
	OCT	0.10	0.18	0.24	0.18	0.16
	NOV	0.10	0.03	0.02	0.14	0.08
	DEC	0.18	0.19	0.06	0.09	0.11
	JAN	0.07	0.34	0.33	0.33	0.19
	FEB	0.05	0.06	0.04	0.06	0.21
	MAR	0.07	0.10	0.10	0.13	0.07
	APR	0.44	0.10	0.21	0.07	0.18
	MR					
	OCT	0.13	0.04	0.27	0.04	0.10
	NOV	0.04	0.05	0.01	0.10	0.04
	DEC	0.22	0.22	0.05	0.21	0.16
	JAN	0.20	0.40	0.21	0.39	0.34
	FEB	0.04	0.14	0.12	0.06	0.18
	MAR	0.16	0.04	0.16	0.07	0.12
	APR	0.22	0.11	0.19	0.13	0.06

during the comparatively rare occurrences of snowpack depth decrease. It is thus not unreasonable to consider such underestimation insignificant and it is also expected that the overestimation described in the following section would have a compensating effect.

(c) Conversion to Water Equivalent

It is necessary to convert the different readings to the same unit of water equivalent in order to obtain a value of precipitation for the 1967-1968 winter for each station. Such conversion is necessary for both snowfall and snowpack data.

It is a widely used though much criticized practice to convert newly fallen snow to water equivalent value by assuming that ten inches of snow would yield one inch of water. Potter called this general use of the 10:1 conversion ratio "unfortunate" and cited studies that had found ratios ranging from 13:1 at Saskatoon to 5:1 in Alberta. (Potter, 1965) However, the 10:1 conversion factor is used in the present study for both newly fallen snow and snowpack data because of the following reasons:

(1) Potter used a ratio to measure the usefulness of the 10:1 conversion factor and produced a map to show its spatial distribution. (Potter, 1965, p. 8). The ratio is

$$\frac{\text{Total measured water content of snow}}{\text{Estimated water equivalent based on 1/10 of total snow}}$$

The value of this ratio for southeastern Alberta and the Cypress Hills area is 0.9.

This means that the use of the 10:1 ratio for the study area would probably lead to about 10% overestimation of precipitation. Sanderson also suggested a 10% error when the 10:1 conversion factor was used. (Sanderson, 1966, p. 30) When one takes into consideration the underestimation mentioned in the previous section, the error involved is likely to be less than the expected 10%.

(2) The snowpack thickness data was taken weekly at the stations. One may argue that it is unreasonable to use the same conversion factor for snowfall reading and snowpack depth. But here one is dealing with the surficial increment of snowpack depth which does not involve the higher density firn layer underneath. In the face of the frequent absence of proper snowfall records, the weekly increments in snowpack depth provide the best approximation.

(3) The 10:1 conversion ratio is easy to apply.

(v) The Results

The results from use of the above estimation method prove satisfactory. The total annual precipitation values

for the various stations in each year of the study period are listed in Table IV. Althought there is no exact criterion to assess the accuracy of these generated data, it is considered that the procedure followed is logical and the estimates realistic and acceptable. A word of qualification may be added here. The estimated monthly winter precipitation has some unrealistic values due to occasional large precipitation events at the base station that affect the distribution ratio. Since winter precipitation normally accumulates until spring snowmelt runoff, the exact monthly distribution of winter precipitation has only secondary importance. Moreover, when using the Thornthwaite Climatic Water Balance procedure, the monthly temperature of any particular winter month has to rise above 30.2°F (-1°C) before runoff starts. This seldom occurred in the study period. The precipitation of winter months accumulated until spring.

TABLE IV

TOTAL ANNUAL PRECIPITATION AT THE 8 STATIONS WITH WINTER PRECIPITATION ESTIMATED

	1968	1969	1970	1971
Station 1	23.3	21.1	21.8	21.6
Station 2	22.0	21.2	21.4	20.5
Station 3	18.8	14.2	21.3	19.7
Station 4	17.4	16.4	20.1	26.9
Station 5	17.7	16.4	20.1	18.0
Station 6	11.9	7.8	14.9	11.1
Station 7	9.0	7.4	13.2	12.1
Station 8	6.9	10.2	8.3	9.4

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